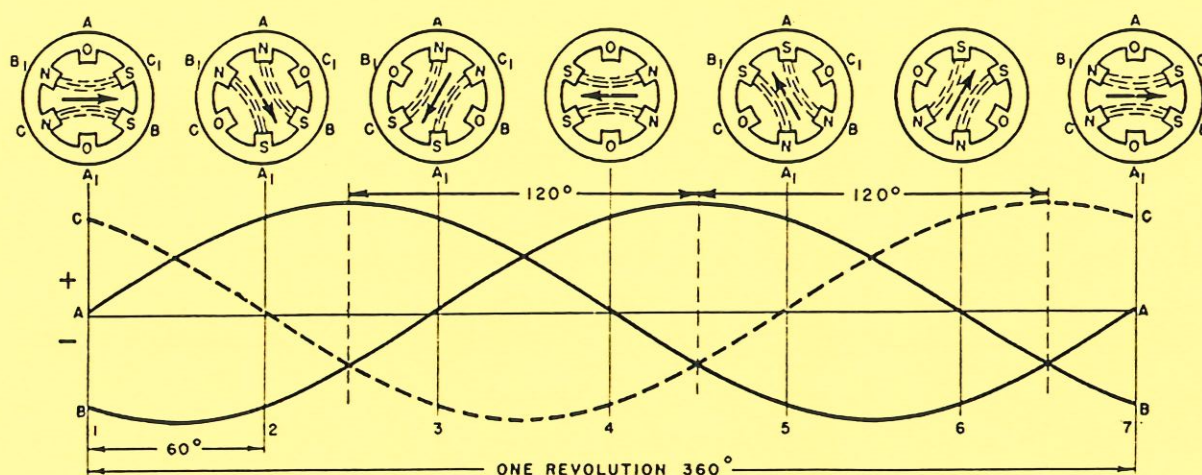
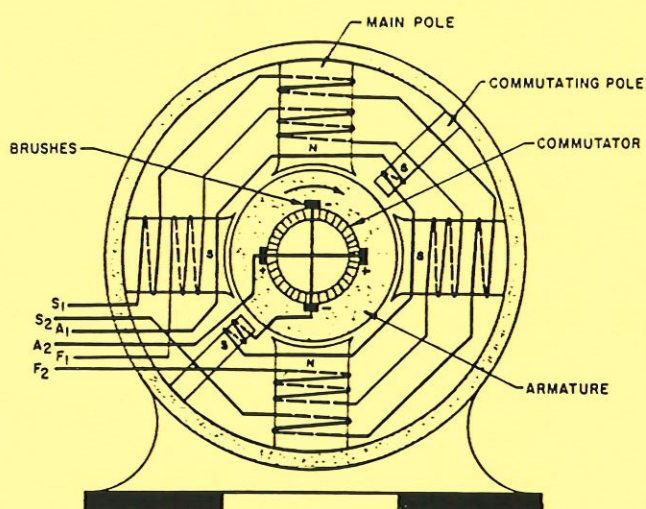

ELECTRICAL SELF-EDUCATION SERIES

BASIC ELECTRICITY II

-MACHINES-



MAINTENANCE & EQUIPMENT TECHNOLOGY
INDIANA HARBOR WORKS-INLAND STEEL CO.

BASIC ELECTRICITY II

-MACHINES-

Book 2 of 2

Qui Docet Discit

The only purpose of this publication is for job training, understanding, and instruction. It has been developed to help prepare an employee not only for the particular job which the employee does or will do, but to provide understanding, knowledge, and information of the function and practice in the general area of operational and maintenance techniques the employee is or will be engaged in. Only periodic updating of this publication will be made. Therefore, at anytime, certain additions or deletions which have occurred recently will not be embodied therein until a later review date. This publication, therefore, is neither a work-book nor a manual for measuring job content nor shall it be construed as a documented listing of work requirements.

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MAINTENANCE & EQUIPMENT
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CHAPTER 12

GENERATORS AND TRANSFORMERS ALTERNATING-CURRENT

A-C Generators

Most of the electric power for use aboard ship and ashore is generated by alternating-current generators. A-c generators are also finding increased use in aircraft, and even automobiles.

A-c generators are made in many different sizes, depending on their intended use. For example, any one of the generators at Boulder Dam can produce millions of volt-amperes, while generators used on aircraft produce only a few thousand volt-amperes.

Regardless of size, however, all generators operate on the same basic principle—a magnetic field cutting through conductors, or conductors passing through a magnetic field. Thus, all generators will have at least two distinct sets of conductors. They are (1) a group of conductors in which the output voltage is generated, and (2) a second group of conductors through which DIRECT CURRENT is passed to obtain an electromagnetic field of fixed direction. The conductors in which the output voltage is generated are always referred to as the ARMATURE WINDINGS. The conductors in which the electromagnetic field originates are always referred to as the FIELD WINDINGS.

In addition to the armature and field, there must also be MOTION between the two. To provide this, a-c generators are built in two major assemblies, the STATOR and the ROTOR. The rotor rotates inside the stator. It may be driven by any one of a number of commonly used power sources, such as gas or hydraulic turbines, electric motors, and steam or internal-combustion engines.

TYPES OF A-C GENERATORS

Revolving Armature

In the revolving-armature a-c generator, the stator provides a stationary electromagnetic

field. The rotor, acting as the armature, revolves in the field, cutting the lines of force, producing the desired output voltage. In this generator, the armature output is taken through sliprings and thus retains its alternating characteristic.

For a number of reasons, the revolving-armature a-c generator is seldom used. Its primary limitation is the fact that its output power is conducted through sliding contacts (sliprings and brushes). These contacts are subject to frictional wear and sparking. In addition, they are exposed, and thus liable to arc-over at high voltages. Consequently, revolving-armature generators are limited to low-power low-voltage applications.

Revolving Field

The revolving-field a-c generator (fig. 12-1) is by far the most widely used type. In this type of generator, direct current from a separate source is passed through windings on the rotor by means of sliprings and brushes. This maintains a rotating electromagnetic field of fixed polarity (similar to a rotating bar magnet). The rotating magnetic field, following the rotor, extends outward and cuts through the armature windings imbedded in the surrounding stator. As the rotor turns, alternating voltages are induced in the windings since magnetic fields of first one polarity and then the other cut through them. Since the output power is taken from stationary windings, the output may be connected through fixed terminals directly to the external loads, as through terminals T1 and T2 in figure 12-1. This is advantageous, in that there are no sliding contacts, and the whole output circuit is continuously insulated, thus minimizing the danger of arc-over.

Sliprings and brushes are still used on the rotor to supply d.c. to the field; they are adequate for this purpose, because the power level

in the field is much lower than in the armature circuit.

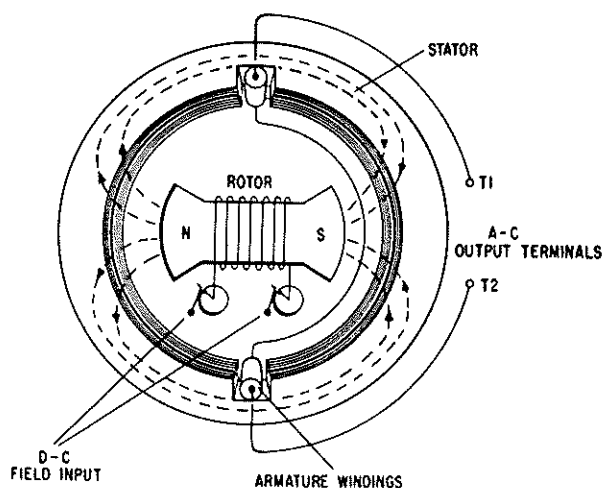


Figure 12-1.—Essential parts of rotating-field a-c generator.

RATING OF A-C GENERATORS

The **RATING** of an a-c generator pertains to the load it is capable of supplying. The normal-load rating is the load it can carry continuously. Its overload rating is the above-normal load which it can carry for specified lengths of time only. The load rating of a particular generator is determined by the internal heat it can withstand. Since heating is caused mainly by current flow, the generator's rating is identified very closely with its **CURRENT** capacity.

The maximum current that can be supplied by an a-c generator depends upon (1) the maximum heating loss (I^2R power loss) that can be sustained in the armature and (2) the maximum heating loss that can be sustained in the field. The armature current varies with the load. This action is similar to that of d-c generators. In a-c generators, however, lagging power-factor loads tend to demagnetize the field, and terminal voltage is maintained only by increasing the d-c field current. Therefore, a-c generators are rated in terms of armature load current and voltage output, or kilovolt-ampere (kv.-a.) output, at a specified frequency and power factor. The specified power factor is usually 80 percent lagging. For example, a single-phase a-c generator designed to deliver 100 amperes at 1,000 volts is rated at 100 kv.-a. This machine would

supply a 100-kw. load at unity power factor or an 80-kw. load at 80 percent power factor. If, however, the a-c generator supplied a 100 kv.a. load at 20 percent power factor, the required increase in d-c field current needed to maintain the desired terminal voltage would cause excessive heating in the field.

Basic Functions of Generator Parts

Almost all rotating-field a-c generators used are actually two generators in one. A typical machine consists of the a-c generator and a smaller d-c generator built in a single unit. The output of the a-c generator section supplies alternating current to the load for which the generator was designed. The d-c generator's only purpose is to supply the direct current required to maintain the a-c generator field. This d-c generator is referred to as the **EXCITER**. A typical a-c generator is shown in figure 12-2 (A); figure 12-2 (B) is a simplified schematic of the generator.

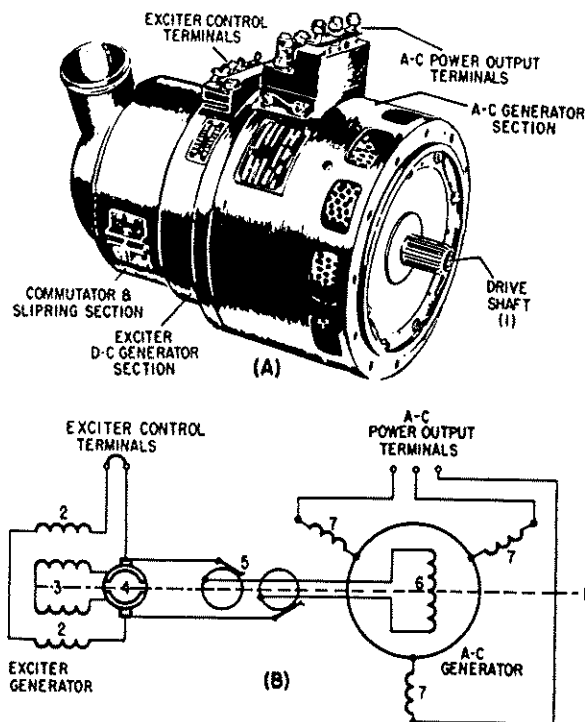


Figure 12-2.—A-c generator and schematic.

Any rotary generator requires a prime moving force (1, fig. 12-2) to rotate the a-c field and exciter armature. This rotary force is trans-

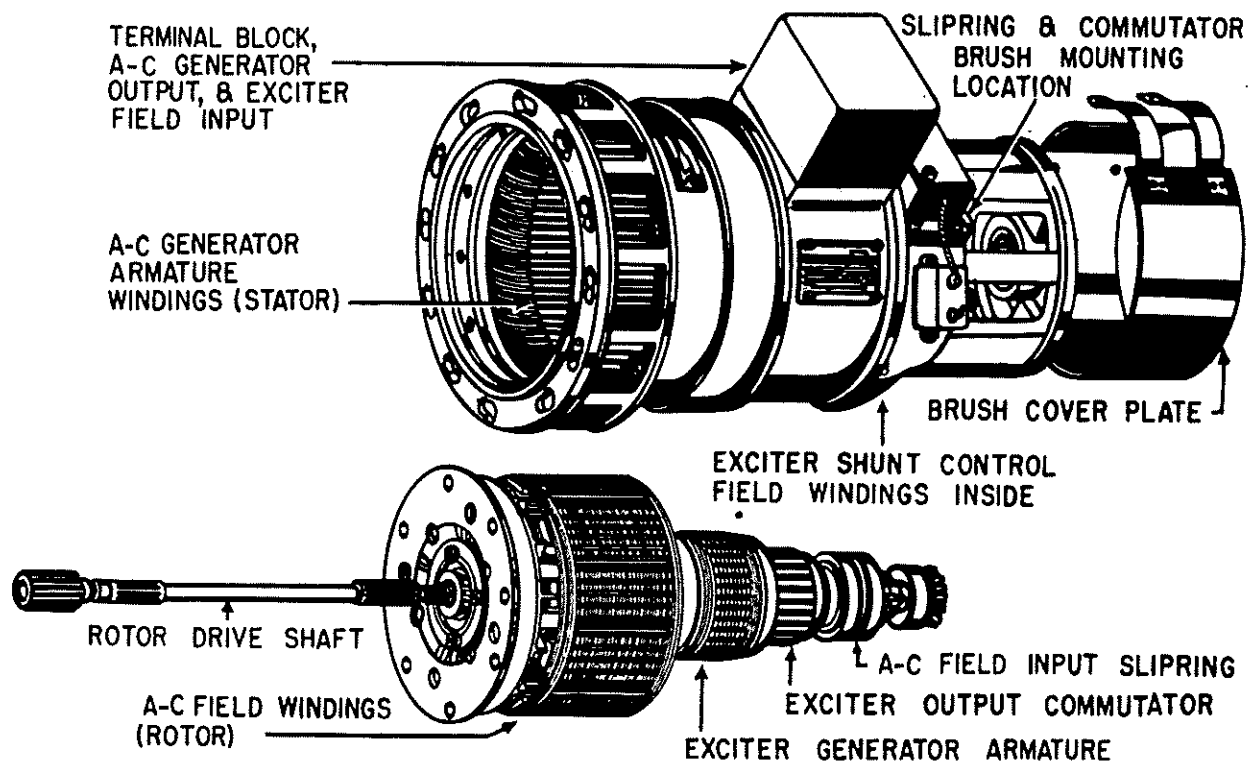


Figure 12-5.—Aircraft a-c generator.

spaced around the stator frame. The rotor has four poles, with adjacent poles of opposite polarity. As the rotor revolves, a-c voltages are induced in the stator windings. Since one rotor pole is in the same position relative to a stator winding as any other rotor pole, all stator polar groups are cut by equal amounts of magnetic lines of force at any given time. As a result, the voltages induced in all the windings have the same amplitude, or value, at any given instant. The four stator windings are connected to each other so that the a-c voltages are in phase, or "series aiding." Assume that rotor pole 1, a south pole, induces a voltage in the direction indicated by the arrow in stator winding 1. Since rotor pole 2 is a north pole, it will induce a voltage in the opposite direction in stator coil 2 with respect to that in coil 1.

In order that the two induced voltages be in series addition, the two coils are connected as shown. Applying the same reasoning, the voltage induced in stator coil 3 (clockwise rotation of the field) is in the same direction (counterclockwise) as the voltage induced in coil 1. Similarly, the direction of the voltage induced in winding 4

is opposite to the direction of the voltage induced in coil 1. All four stator coil groups are connected in series so that the voltages induced in each winding add to give a total voltage that is four times the voltage in any one winding.

TWO-PHASE GENERATORS

Multiphase or polyphase a-c generators have two or more single-phase windings symmetrically spaced around the stator. In a 2-phase a-c generator there are two single-phase windings physically spaced so that the a-c voltage induced in one is 90° out of phase with the voltage induced in the other. The windings are electrically separate from each other. When one winding is being cut by maximum flux, the other is being cut by no flux. This condition establishes the 90° relation between the two phases.

Figure 12-7 is a schematic diagram of a 2-phase 4-pole a-c generator. The stator consists of two single-phase windings (phases) completely separated from each other. Each phase is made up of four windings, which are connected in series so that their voltages add. The rotor

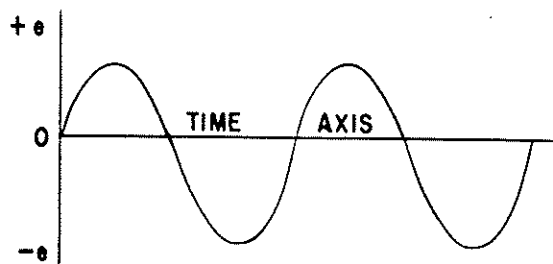
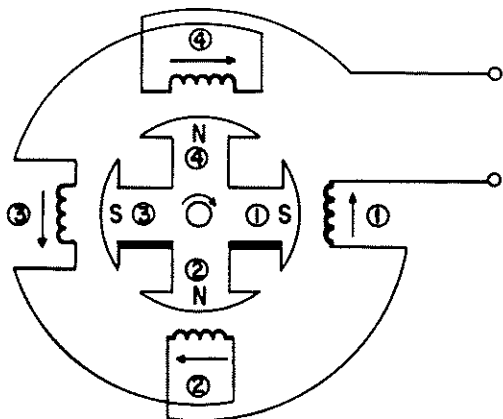
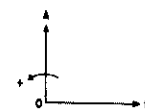
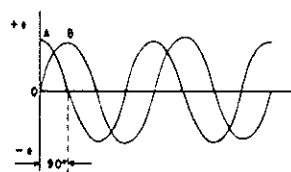
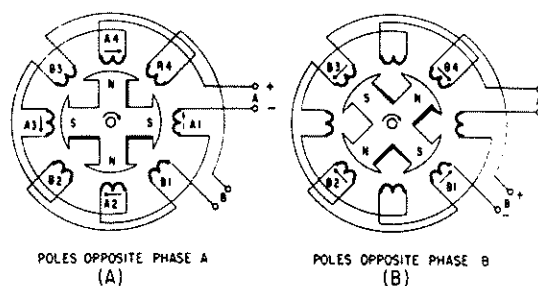


Figure 12-6.—Single-phase a-c generator.

is identical with that used in the single-phase a-c generator. In figure 12-7 (A), the rotor poles are opposite all of the coils of phase A. Therefore, the voltage induced in phase A is maximum and the voltage induced in phase B is zero. As the rotor continues rotating in a clockwise direction, it moves away from the windings of phase A and approaches those of phase B. As a result, the voltage in phase A decreases from its maximum value and the voltage in phase B increased from zero. In figure 12-7 (B), the rotor poles are opposite the windings of phase B. Now the voltage induced in phase B is maximum; whereas the voltage induced in phase A has dropped to zero. Notice that in the 4-pole a-c generator a 45° mechanical rotation of the rotor corresponds electrically to one quarter cycle, or 90 electrical degrees. Figure 12-7 (C) illustrates the wave-forms of the voltage generated in each of the two phases. Both are sine curves, and A leads B by 90°. Figure 12-7 (D) illustrates the vectors representing the 2-phase voltages. Vector A leads vector B by 90°.



WAVE FORMS
(C)

VECTORS
(D)

Figure 12-7.—Two-phase four-pole a-c generator.

The two phases of a 2-phase a-c generator can be connected to each other as shown in figure 12-8, so that only three leads are brought out to the load. The a-c generator is then called a 2-phase 3-wire a-c generator. The two phases for a 4-pole a-c generator are shown in figure 12-8 (A). A simplified schematic diagram is shown in figure 12-8 (B), in which the rotor is omitted and each phase is indicated as a single coil. The two coils are drawn at right angles to each other to represent the 90° phase displacement between their respective voltages. The three wires make possible three different load connections—(A) and (B) across phases A and

B, respectively, and (C) across both phases in series. The third voltage (C) is displaced 45° from the A and B phase voltages and is their vector sum. If each phase voltage has an effective value of 100 volts, the vector sum of these voltages will be the hypotenuse of a right triangle, the base and altitude of which are each 100 volts. This hypotenuse is equal to

$$\frac{100}{\cos 45^\circ}, \text{ or } \frac{100}{0.707} = 141 \text{ volts.}$$

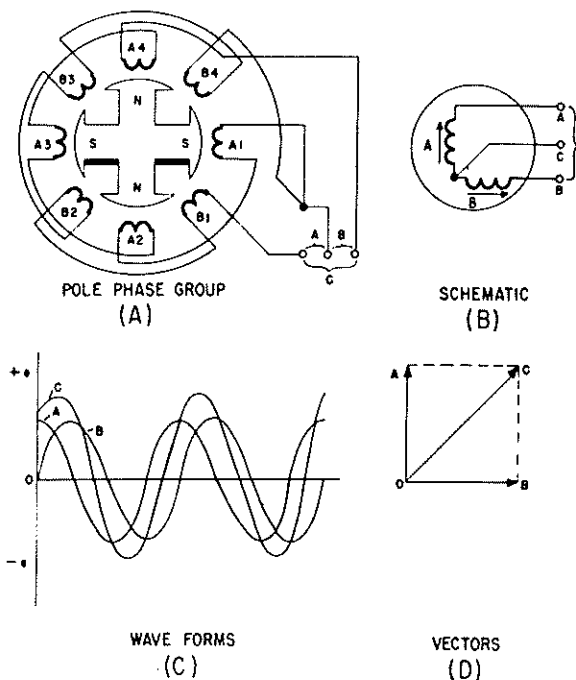


Figure 12-8. Two-phase three-wire a-c generator.

THREE-PHASE GENERATORS

The 3-phase a-c generator, as the name implies, has three single-phase windings spaced so that the voltage induced in each winding is 120° out of phase with the voltages in the other two windings. A schematic diagram of a 3-phase stator showing all the coils becomes complex, and it is difficult to see what is actually happening. A simplified schematic diagram, showing all the windings of a single phase lumped together as one winding, is illustrated in figure 12-9 (A). The rotor is omitted for simplicity. The waveforms of voltage are shown to the right of the schematic. The three voltages are 120° apart and are similar to the voltages that would be generated by three single-phase a-c generators whose voltages are out of phase by angles of 120° . The three phases are independent of each other.

The Wye Connection

Rather than have six leads come out of the 3-phase a-c generator, one of the leads from each phase may be connected to form a common junction. The stator is then called WYE, or STAR, connected. The common lead may or may not be

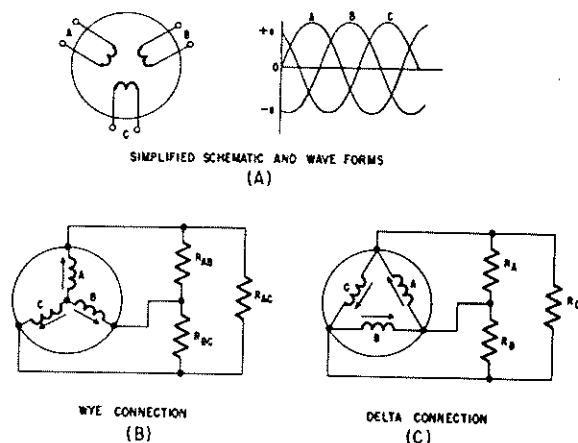


Figure 12-9. Three-phase a-c generator

brought out of the machine. If it is brought out, it is called the NEUTRAL. The simplified schematic (fig. 12-9(B)) shows a wye-connected stator with the common lead not brought out. Each load is connected across two phases in series. Thus, R_{ab} is connected across phases A and B in series, R_{ac} is connected across phases A and C in series, and R_{bc} is connected across phases B and C in series. Thus, the voltage across each load is larger than the voltage across a single phase. In a wye-connected a-c generator the three start ends of each single-phase winding are connected together to a common neutral point and the opposite, or finish, ends are connected to the line terminals A, B, and C. These letters are always used to designate the three phases of a 3-phase system, or the three line wires to which the a-c generator phases connect. A 3-phase wye-connected a-c generator supplying three separate loads is shown in figure 12-10 (A). When unbalanced loads are used, a neutral may be added as shown in the figure by the broken line between the common neutral point and the loads. The neutral wire serves as a common return circuit for all three phases and maintains a voltage balance across the loads. No current flows in the neutral wire when the loads are balanced. This system is a 3-phase 4-wire circuit and is used to distribute 3-phase power to shore-based installations. The 3-phase 4-wire system is not used aboard ship, but is widely used in industry and for aircraft a-c power systems.

The phase relations in a 3-wire 3-phase wye-connected system are shown in figure 12-10 (B). In constructing vector diagrams of 3-phase

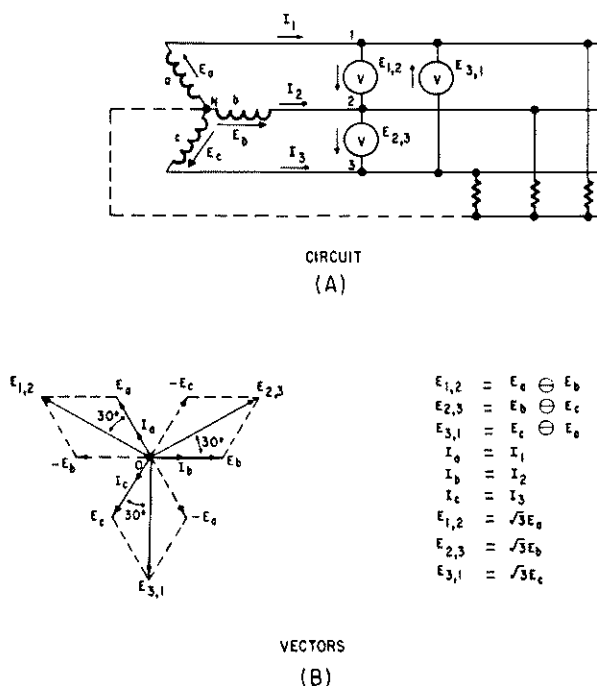


Figure 12-10.—Three-phase wye-connected system.

circuits, a counterclockwise rotation is assumed in order to maintain the correct phase relation between line voltages and currents. Thus, the a-c generator is assumed to rotate in such a direction as to generate the three phase voltages in the order, E_a , E_b , E_c .

The voltage in phase b , or E_b , lags the voltage in phase a , or E_a , by 120° . Likewise, E_c lags E_b by 120° , and E_a lags E_c by 120° . In figure 12-10 (A), the arrows E_a , E_b , and E_c , represent the positive direction of generated voltage in the wye-connected a-c generator. The arrows I_1 , I_2 , and I_3 represent the positive direction of phase and line currents supplied to balanced unity power-factor loads connected in wye. The three voltmeters connected between lines 1-2, 2-3, and 3-1, respectively, indicate effective values of line voltage. The line voltage is greater than the voltage of a phase in the wye-connected circuit because there are two phases connected in series between each pair of line wires, and their voltages combine. Line voltage is not twice the value of phase voltage, however, because the phase voltages are not in phase with each other.

The relation between phase and line voltages is shown in the vector diagram. Effective values

of phase voltage are indicated by vectors, E_a , E_b , and E_c . Effective values of line and phase current are indicated by vectors I_a , I_b , and I_c . Because there is only one path for current between any given phase and the line wire to which it is connected, the phase current is equal to the line current. The respective phase currents have equal values because the load is assumed to be balanced. For the same reason, the respective line currents have equal values. When the load has unity power factor, the phase currents are in phase with their respective phase voltages.

In combining a-c voltages it is necessary to know the DIRECTION in which the positive maximum values of the voltages act in the circuit as well as the MAGNITUDES of the voltages. For example, in figure 12-11 (A), the positive maximum voltage generated in coils A and B act in the direction of the arrows, and B leads A by 120° . This arrangement may be obtained by assuming coils A and B to be two armature windings located 120° apart. If each voltage has an effective value of 100 volts, the total voltage is $E_T = 100$ volts, as shown by the polar vectors in figure 12-11 (B).

If the connections of coil B are reversed (fig. 12-11 (C)) with respect to their original connections, the two voltages will be in opposition, as will be seen by tracing around the circuit in the direction of the arrow in coil A . The positive direction of the voltage in coil B is opposite to the direction of the trace; the positive direction of the voltage generated in coil A is the same as that of the trace; hence, the two voltages are in opposition. This effect is the same as though the positive maximum value of E_b were 60° out of phase with that of E_a , and E_b acted in the same direction as E_a when the circuit trace was made (fig. 12-11 (D)) to vector E_a is accomplished by reversing the position of E_b from that shown in figure 12-11 (B) to the position shown in figure 12-11 (D) and completing the parallelogram. If E_a and E_b are each 100 volts, $E_T = \sqrt{3} \times 100$, or 173 volts. The value of E_T may be derived in the following manner: Erecting a perpendicular to E_T divides the isosceles triangle into two equal right triangles each having a hypotenuse of 100 volts and a base of $100 \cos 30^\circ$, or 86.6 volts. The total length of E_T is 2×86.6 , or 173.2 volts.

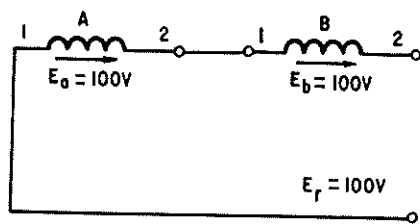
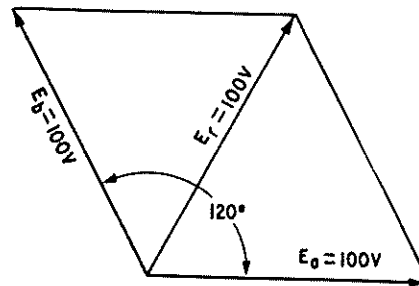
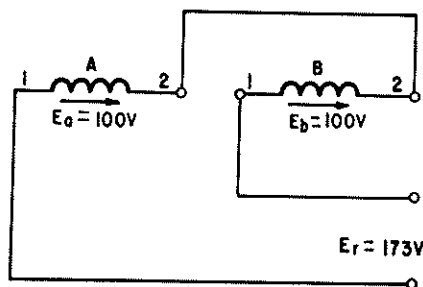
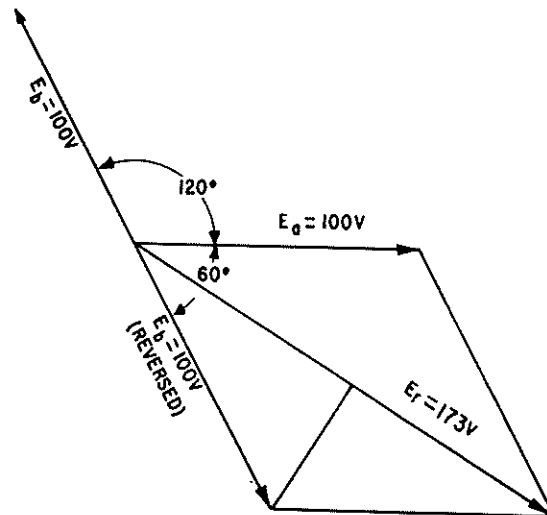

 (A) POSITIVE VOLTAGES
SAME DIRECTION

 (B) E_b LEADS E_a BY 120°

 (C) POSITIVE VOLTAGES
IN OPPOSITE DIRECTION

 (D) (REVERSED) E_b LAGS E_a BY 60°

Figure 12-11.—Vector analysis of voltages in series aiding and opposing.

To construct the line voltage vectors $E_{1,2}$, $E_{2,3}$, and $E_{3,1}$, in figure 12-10, it is first necessary to trace a path around the closed circuit which includes the line wires, armature windings, and one of the three voltmeters. For example, in figure 12-10 (A), consider the circuit that includes the upper and middle wires, the voltmeter connected across them, and the a-c generator phases a and b . The circuit trace is started at the center of the wye, proceeds through phase a of the a-c generator, out line 1, down through the voltmeter from line 1 to line 2, and through phase b of the a-c generator back to the starting point. Voltage drops along line wires are disregarded. The voltmeter indicates an effective value equal to the vector sum of the effective value of voltage in phases a and b . This value is the line voltage, $E_{1,2}$. According to Kirchhoff's law, the source voltage between lines

1 and 2 equals the voltage drop across the voltmeter connected to these lines.

If the direction of the path traced through the GENERATOR is the SAME as that of the arrow, the sign of the voltage is PLUS; if the direction of the trace is OPPOSITE to the arrow, the sign of the voltage is MINUS. If the direction of the path traced through the VOLTMETER is the SAME as that of the arrow, the sign of the voltage is MINUS; if the direction of the trace is OPPOSITE to that of the arrow, the sign of the voltage is PLUS.

The following equations for voltage are based on the preceding rules:

$$E_a \oplus (-E_b) = E_{1,2}, \text{ or } E_{1,2} = E_a \ominus E_b.$$

$$E_b \oplus (-E_c) = E_{2,3}, \text{ or } E_{2,3} = E_b \ominus E_c.$$

$$E_c \oplus (-E_a) = E_{3,1}, \text{ or } E_{3,1} = E_c \ominus E_a.$$

The signs $\oplus$ and $\ominus$ mean vector addition and vector subtraction, respectively. One vector is subtracted from another by reversing the position of the vector to be subtracted through an angle of 180° and constructing a parallelogram, the sides of which are the reversed vector and the other vector. The diagonal of the parallelogram is the difference vector.

These equations are applied to the vector diagram of figure 12-10 (B), to derive the line voltages $E_{1,2}$, $E_{2,3}$, and $E_{3,1}$, as the diagonals of three parallelograms of which the sides are the phase voltages E_a , E_b , and E_c . From this vector diagram, the following facts are observed: (1) The line voltages are equal and 120° apart; (2) the line currents are equal and 120° apart; (3) the line currents are 30° out of phase with the line voltages when the power factor of the load is 100 percent; and (4) line voltage is the product of the phase voltage and $\sqrt{3}$.

The Delta Connection

A three-phase stator may also be connected as shown in figure 12-9 (C). This is called the DELTA connection. In a delta-connected a-c generator, the start end of one phase winding is connected to the finish end of the third; and the start end of the third, to the finish end of the first. The three junction points are connected to the line wires leading to the load. A 3-phase delta-connected a-c generator is represented at the left (fig. 12-12 (A)). The generator is connected to a 3-phase 3-wire circuit which supplies a 3-phase delta-connected load at the right-hand end of the 3-phase line. Because the phases are connected directly across the line wires, phase voltage is equal to line voltage. When the generator phases are properly connected in delta, no appreciable current flows within the delta loop when there is no external load connected to the generator. If any one of the phases is reversed with respect to its correct connection, a short-circuit current will flow within the windings on no load, causing damage to the windings.

To avoid connecting a phase in reverse it is necessary to test the circuit before closing the delta. This may be done by connecting a voltmeter or fuse wire between the two ends of the delta loop before closing the delta. The two ends of the delta loop should never be connected if there is an indication of any appreciable current or voltage between them when no load is connected to the generator.

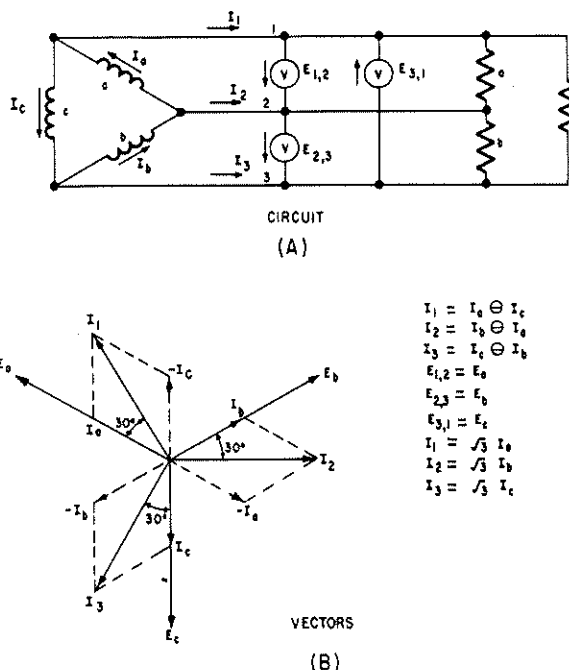


Figure 12-12.—Three-phase delta-connected system.

The three phase currents, I_a , I_b , and I_c , are indicated by accompanying arrows in the generator phases at the left in figure 12-12 (A). These arrows point in the direction of the positive current and voltage of each phase. The three voltmeters connected across lines 1-2, 2-3, and 3-1, respectively, indicate effective values of line and phase voltage. Line current I_1 is supplied by phases a and c , which are connected to line 1. Line current is greater than phase current, but not twice as great because the phase currents are not in phase with each other. The relation between line currents and phase currents is shown in figure 12-12 (B).

Effective values of line and phase voltages are indicated by vectors E_a , E_b , and E_c . Note that the vector sum of E_a , E_b , and E_c is zero. The phase currents are equal to each other because the loads are balanced. The line currents are equal to each other for the same reason. At unity-power-factor loads, the phase current and phase voltage have a 0° angle between them.

To construct the line current vectors it is first necessary to consider the direction of currents at the junctions of the line wires and the generator phases. Consider the junction formed by phase a , phase c , and line 1. According to Kirchhoff's law, line current I_1 is equal to the

vector difference between I_a and I_c . In figure 12-12 (B), current vector I_a is in the same general direction as current vector I_1 (less than 90° displaced from I_1), and current vector I_c is in opposition to vector I_1 (more than 90° displaced from it). I_1 is the vector sum of I_a and $-I_c$. These are two equal values of phase current and they are 60° out of phase with each other. The vector sum of all the currents entering and leaving the junction is zero. Current arrows that point toward the junction are considered to represent positive currents. Current arrows that point away from the junction are considered to represent negative currents. The following equations for current are based on the preceding rules:

$$I_a \oplus (-I_c) = I_1, \text{ or } I_1 = I_a \oplus I_c.$$

$$I_b \oplus (-I_a) = I_2, \text{ or } I_2 = I_b \oplus I_a.$$

$$I_c \oplus (-I_b) = I_3, \text{ or } I_3 = I_c \oplus I_b.$$

Here also, the signs $\oplus$ and $\ominus$ mean vector addition and vector subtraction, respectively. Vector subtraction is accomplished again by reversing the vector being subtracted through an angle of 180° and combining it with the other vector by the parallelogram method to form the diagonal which is the vector difference.

If the current equations are applied to the vector diagram of figure 12-12 (B), the line current I_1 , I_2 , and I_3 are derived as diagonals of the three parallelograms in which the sides are the phase currents I_a , I_b , and I_c . From this diagram the following facts are observed: (1) The line currents are equal and 120° apart; (2) the line voltages are equal and 120° apart; (3) the line currents are 30° out of phase with the line voltages when the power factor of the load is unity; and (4) the line current is equal to the product of the phase current and $\sqrt{3}$.

The power delivered by a balanced 3-phase wye-connected system is equal to three times the power delivered by each phase. The total true power is

$$P_t = 3E_{\text{phase}}I_{\text{phase}} \cos \theta$$

Because $E_{\text{phase}} = \frac{E_{\text{line}}}{\sqrt{3}}$ and $I_{\text{phase}} = I_{\text{line}}$,

the total true power is

$$\begin{aligned} P_t &= 3 \frac{E_{\text{line}}}{\sqrt{3}} I_{\text{line}} \cos \theta, \\ &= \sqrt{3} E_{\text{line}} I_{\text{line}} \cos \theta. \end{aligned}$$

The power delivered by a balanced 3-phase delta-connected system is also three times the power delivered by each phase.

Because $E_{\text{phase}} = E_{\text{line}}$ and $I_{\text{phase}} = \frac{I_{\text{line}}}{\sqrt{3}}$

the total true power is

$$\begin{aligned} P_t &= 3E_{\text{line}} \frac{I_{\text{line}}}{\sqrt{3}} \cos \theta, \\ &= \sqrt{3} E_{\text{line}} I_{\text{line}} \cos \theta. \end{aligned}$$

Thus, the expression for 3-phase power delivered by a balanced delta-connected system is the same as the expression for 3-phase power delivered by a balanced wye-connected system. Two examples are given to illustrate the phase relations between current, voltage, and power in (1) a 3-phase wye-connected system and (2) a 3-phase delta-connected system.

Example 1: A 3-phase wye-connected a-c generator has a terminal voltage of 450 volts and delivers a full-load current of 300 amperes per terminal at a power factor of 80 percent. Find (a) the phase voltage, (b) the full-load current per phase, (c) the kilovolt-ampere, or apparent power, rating, and (d) the true power output.

$$(a) E_{\text{phase}} = \frac{E_{\text{line}}}{\sqrt{3}} = \frac{450}{\sqrt{3}} = 260 \text{ volts.}$$

$$(b) I_{\text{phase}} = I_{\text{line}} = 300 \text{ amperes.}$$

$$\begin{aligned} (c) \text{ Apparent power} &= \sqrt{3} E_{\text{line}} I_{\text{line}} \\ &= \sqrt{3} \times 450 \times 300 = 233,600 \text{ va., or} \\ &\quad 233.6 \text{ kv.-a.} \end{aligned}$$

$$\begin{aligned} (d) \text{ True power} &= \sqrt{3} E_{\text{line}} I_{\text{line}} \cos \theta \\ &= \sqrt{3} \times 450 \times 300 \times 0.8 \\ &= 186,000 \text{ watts, or } 186.8 \text{ kw.} \end{aligned}$$

Example 2: A 3-phase delta-connected a-c generator has a terminal voltage of 450 volts and the current in each phase is 200 amperes. The power factor of the load is 75 percent. Find (a) the line voltage, (b) the line current, (c) the apparent power, and (d) the true power.

- (a) $E_{\text{phase}} = E_{\text{line}} = 450$ volts.
- (b) $I_{\text{line}} = \sqrt{3} I_{\text{phase}} = 1.732 \times 200 = 346$ amperes.
- (c) Apparent power $= \sqrt{3} E_{\text{line}} I_{\text{line}}$
 $= 1.732 \times 450 \times 346 = 269,000$ va., or 269 kv.-a.
- (d) True power $= \sqrt{3} E_{\text{line}} I_{\text{line}} \cos \theta$
 $= 1.732 \times 450 \times 346 \times 0.75$
 $= 201,700$ watts, or 201.7 kw.

MEASUREMENT OF POWER

The wattmeter connections for measuring the true power in a 3-phase system are shown in figure 12-13. The method shown in figure 12-13 (A) uses three wattmeters with their current coils inserted in series with the line wires and their potential coils connected between line and neutral wires. The total true power is equal to the arithmetic sum of the three wattmeter readings.

The method shown in figure 12-13 (B) uses two wattmeters with their current coils connected in series with two line wires and their potential coils connected between these line wires and the common, or third, wire that does not contain the current coils. The total true power is equal to the algebraic sum of the two wattmeter readings. If one meter reads backward, its potential coil connections are first reversed to make the meter read up-scale and the total true power is then equal to the difference in the two wattmeter readings. If the load power factor is less than 0.5 and the loads are balanced, the total true power will be equal to the difference in the two wattmeter readings. If the load power factor is 0.5, one meter will indicate the total true power and the other will indicate zero. If the load power factor is above 0.5, the total true power is equal to the sum of the two wattmeter readings.

FREQUENCY

The frequency of the a-c generator voltage depends upon the speed of rotation of the rotor and the number of poles. The faster the speed, the higher the frequency will be; and the lower the speed, the lower the frequency becomes. The more poles there are on the rotor, the higher the frequency will be for a given speed. When a rotor has rotated through an angle such that two adjacent rotor poles (a north and a south pole) have passed one winding, the voltage induced in that winding will have varied through one complete cycle. For a given frequency, the more pairs of poles there are, the lower will be the speed of rotation. A 2-pole generator rotates at

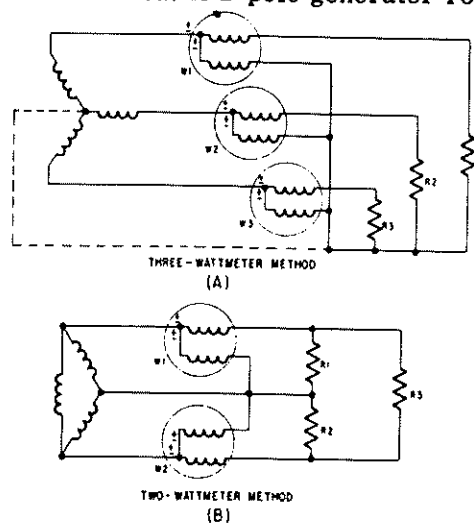


Figure 12-13.—Wattmeter connection for measurement of power in a 3-phase system.

twice the speed of a 4-pole generator for the same frequency of generated voltage. The frequency of the generator in cycles per second is related to the number of poles and the speed, as expressed by the equation

$$f = \frac{P}{2} \times \frac{N}{60} = \frac{PN}{120}$$

where P is the number of poles and N the speed in r.p.m. For example, a 2-pole 3,600 r.p.m. generator has a frequency of $\frac{2 \times 3,600}{120} = 60$ cycles per second; a 4-pole 1,800-r.p.m. generator has the same frequency; and a 6-pole 500-r.p.m. generator has a frequency of $\frac{6 \times 500}{120} = 25$ cycles per second, and a 12-pole 4,000 r.p.m. generator has a frequency of $\frac{12 \times 4,000}{120} = 400$ cycles per second.

GENERATED VOLTAGE

Once the machine has been designed and built, the generated voltage of an a-c generator is controlled, in practice, by varying the d-c excitation voltage applied to the field winding.

In the design, however, many factors must be taken into account, as the following text illustrates.

As mentioned before, the conductors in a generator armature are arranged in one or more groups called phases, according to whether the machine is designed to deliver single-phase, 2-phase, or 3-phase voltages. The effective voltage, E , per phase is

$$E = 2.22 \Phi Z f 10^{-8} K_b K_p,$$

where Φ is the number of magnetic lines of flux per pole, Z the number of conductors in series per phase, f the frequency in cycles per second, K_b a breadth (or belt) factor, and K_p a pitch factor.

Generally, the coils of each phase are distributed uniformly around the stator. The voltages generated in the various coils are not in time phase with each other because of the displacement of the coils. A breadth, or belt, factor K_b takes the displacement into account and reduces the total generated voltage per phase below the voltage that would be generated if all the active conductors were in the form of a concentrated winding. Also, if the two halves of a coil are less than 180 electrical degrees apart, the voltage generated in the coil is less than it would be if the coil pitch were a full 180 electrical degrees. The pitch factor, K_p , accounts for this reduction in voltage.

For example, a certain 3-phase, 60-cycle generator has 96 conductors in series per phase and a field pole flux of 2.54×10^6 lines per pole. The breadth factor is 0.958, and the pitch factor is 0.966. The effective voltage per phase is

$$E = \frac{2.22 \times 2.54 \times 10^6 \times 96 \times 60 \times 0.958 \times 0.966}{10^8} = 300 \text{ volts.}$$

CHARACTERISTICS

When the load on a generator is changed, the terminal voltage varies with the load. The amount of variation depends on the design of the generator and the power factor of the load. With a load having a lagging power factor, the drop in terminal voltage with increased load is greater than for unity power factor. With a load having a leading power factor, the terminal voltage tends to rise. The causes of a change in terminal voltage with load change are (1) armature resistance, (2) armature reactance, and (3) armature reaction.

Armature Resistance

When current flows through a generator armature winding, there is an IR drop due to the resistance of the winding. This drop increases with load, and the terminal voltage is reduced. The armature resistance drop is small because the resistance is low.

Armature Reactance

The armature current of an a-c generator varies approximately as a sine wave. The continuously varying current in the generator armature is accompanied by an IX_L voltage drop in addition to the IR drop. Armature reactance in an a-c generator may be from 30 to 50 times the value of armature resistance because of the relatively large inductance of the coils compared with their resistance.

A simplified series equivalent circuit of one phase of an a-c generator is shown in figure 12-14. The voltage generated in the phase winding is equal to the vector sum of the terminal voltage for the phase and the internal voltage loss in the armature resistance, R , and the armature reactance, X_L , associated with that phase. The voltage vectors for a unity power-factor load are shown in figure 12-14 (A). The armature IR drop is in phase with the current, I , and the terminal voltage, E_t . Because the armature IX_L drop is 90° out of phase with the current, the terminal voltage is approximately equal to the generated voltage, less the IR drop in the armature.

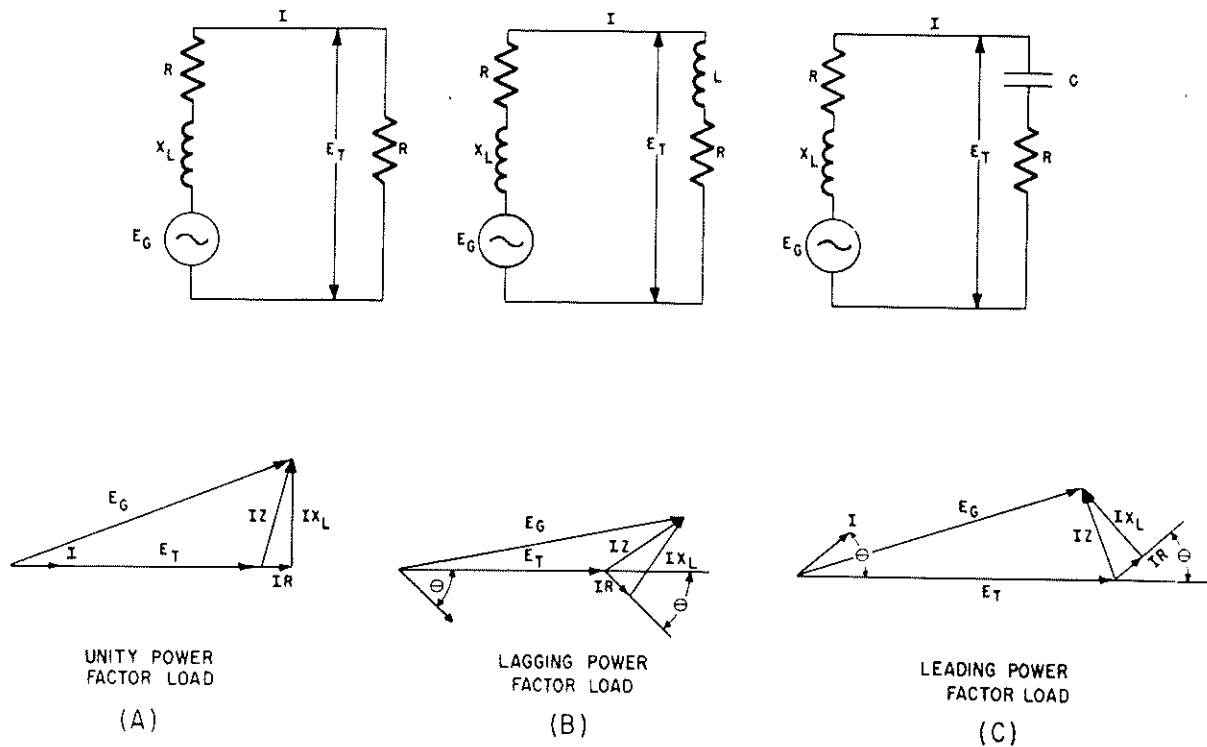


Figure 12-14.—A-c generator voltage characteristics.

The voltage vectors for a lagging power-factor load are shown in figure 13-14 (B). The load current and IR drop lag the terminal voltage by angle θ . In this example, the armature IZ drop is more nearly in phase with the terminal voltage and the generated voltage. Hence, the terminal voltage is approximately equal to the generated voltage, less the armature IZ drop. Because the IZ drop is much greater than the IR drop, the terminal voltage is reduced that much more. The voltage vectors for a leading power-factor load are shown in figure 12-14 (C). The load current and IR drop lead the terminal voltage by angle θ . This condition results in an increase in terminal voltage above the value of E_g . The total available voltage of the a-c generator phase is the combined effect of E_g (rotationally induced) and the self-induced E_g voltage (not shown in the vectors). The self-induced voltage, as in any a-c circuit, is caused by the varying field (accompanying the varying armature current) linking the armature conductors. The self-induced voltage always lags the current by 90° ; hence, when I leads E_t , the self-induced voltage aids E_g , and E_t increases.

Armature Reaction

When an a-c generator supplies no load, the d-c field flux is distributed uniformly across the air gap. When an a-c generator supplies a reactive load, however, the current flowing through the armature conductors produces an armature magnetomotive force (m.m.f.) that influences the terminal voltage by changing the magnitude of the field flux across the air gap. When the load is inductive, the armature m.m.f. opposes the d-c field and weakens it, thus lowering the terminal voltage. When a leading current flows in the armature, the d-c field is aided by the armature m.m.f. and the flux across the air gap is increased, thus increasing the terminal voltage.

VOLTAGE REGULATION

The voltage regulation of an a-c generator is the change of voltage from full load to no load, expressed in percentage of full-load volts, when the speed and d-c field current are held constant.

$$\text{Percent regulation} = \frac{E_{NL} - E_{FL}}{E_{FL}} \times 100.$$

For example, the no-load voltage of a certain generator is 250 volts and the full-load voltage is 220 volts. The percent regulation is

$$\frac{250 - 220}{220} \times 100 = 13.6 \text{ percent.}$$

PRINCIPLES OF A-C VOLTAGE CONTROL

In an a-c generator, an alternating voltage is induced into the armature windings when magnetic fields of alternating polarity are passed across these windings. The amount of voltage induced into the a-c generator windings depends mainly on three things: the number of conductors in series per winding, the speed at which the magnetic field passes across the winding (generator r.p.m.), and the strength of the magnetic field. Any of these three could conceivably be used to control the amount of voltage induced into the a-c generator windings.

The number of windings, of course, is fixed when the generator is manufactured. Also, if the frequency of a generator's output is required to be of a constant value, then the speed of the rotating field must be held constant. This prevents the use of the generator r.p.m. as a means of controlling the voltage output. Thus, the only practical remaining method for obtaining voltage control is to control the strength of the rotating magnetic field. In some specialized applications, the field is furnished by a permanent magnet. The a-c generator in figure 12-2 uses an electromagnetic field rather than a permanent magnetic type field. The strength of this electromagnetic field may be varied by changing the amount of current flowing through the coil. This is done by varying the amount of voltage applied across the coil. It can be seen that by varying the exciter armature d-c output voltage, the a-c generator field strength is also varied. Thus, the magnitude of the generated a-c voltage depends directly on the value of the exciter output voltage. This relationship allows a relatively large a-c voltage to be controlled by a much smaller d-c voltage.

The next function of the a-c generator that you should understand is how the d-c exciter output voltage is controlled. Voltage control in a d-c generator is obtained by varying the strength

of the d-c generator shunt field. This is done by using any of a number of different types of voltage regulators. A device which will vary the exciter shunt field current in accordance with changes in the a-c generator voltage is called an a-c generator voltage regulator. This regulator must also maintain the correct value of exciter shunt field current when no a-c voltage corrective action is required (steady state output). In figure 12-15, note that a pair of connections labeled A-C SENSING INPUT feeds a voltage proportional to the a-c generator output voltage to the A-C VOLTAGE REGULATOR. Note also that a portion of the exciter armature output is connected through the exciter's field rheostat, *RX*, then through the exciter shunt field windings, and finally back to the exciter armature. Obviously, the exciter supplies direct current to its own control field, in addition to the a-c generator field, as determined by the setting of *RX*. The setting of *RX* is controlled by the magnetic strength of the control coil *L*. The magnetic strength of *L* is, in turn, controlled by the voltage across resistor *R*. The voltage across *R* is rectified d. c., and is proportional to the a-c line voltage. (Rectifiers are devices that change a.c. to d.c.)

Thus, the essential function of the voltage regulator is to use the a-c output voltage, which it is designed to control, as a sensing influence to control the amount of current the exciter supplies to its own control field. A drop in the output a-c voltage will change the setting of *RX* in one direction and cause a rise in the exciter control field current. A rise in the output a-c voltage will change the setting of *RX* in the opposite direction and cause a drop in the exciter control field current. These latter two characteristics are caused by actions within the voltage regulator. These characteristics are common to both the resistive and magnetic (magnetic amplifier) types of a-c voltage regulators. Both types of regulators perform the same functions, but accomplish them through different operating principles. A detailed description of the construction and operating principles of any particular type of voltage regulator is best left to courses concerning specific ratings, such as the EM and AE courses.

PARALLEL OPERATION OF A-C GENERATORS

A-c generators are connected in parallel to (1) increase the plant capacity beyond that of a single unit, (2) serve as additional reserve power

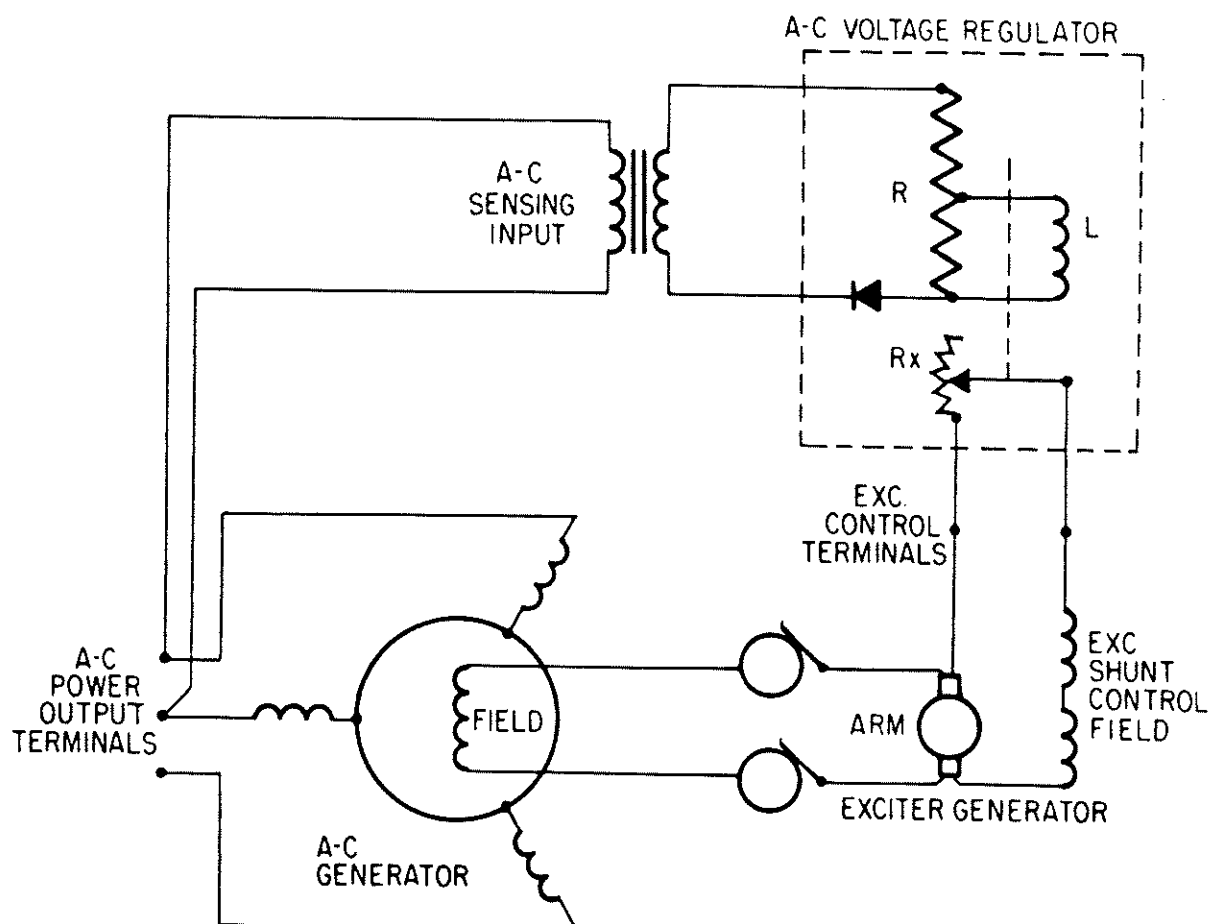


Figure 12-15.—Simplified voltage regulator circuit.

for expected demands, or (3) permit shutting down one machine and cutting in a standby machine without interrupting the power supply. When a-c generators are of sufficient size, and are operating at unequal frequencies and terminal voltages, severe damage may result if they are suddenly connected to each other through a common bus. To avoid this, the generators must be synchronized as closely as possible **BEFORE** connecting them together. This is done by connecting one generator to the bus (referred to as the **BUS GENERATOR**), and then synchronizing the other (**INCOMING generator**) to it before closing the incoming generator's main power contactor. The generators are synchronized when the following conditions are set:

1. Equal terminal voltages. This is obtained by adjustment of the incoming generator's field strength.

2. Equal frequency. This is obtained by adjustment of the incoming generator's prime mover speed.

3. Phase voltages in proper phase relation. (Connecting phase voltages must reach peak values of the same polarity at the same instant.) The generators could have the same frequency, and still not be **IN STEP**. That is, if the two generators have the same frequency, but one is lagging the other, the lagging generator will remain a fixed number of degrees behind the leading generator, until it is accelerated slightly to **CATCH UP**.

4. Phases connected in proper sequence. One pair of phases may be properly connected, while the other two pairs may be crossed. In this case, the phase sequence of one generator may be **ACB**, while the other is **ABC**.

Synchronizing, A-C Generators

All of the foregoing conditions may be set by the following methods:

Equal voltages may be checked by using a voltmeter. The remaining conditions, equal frequency, phase relations, and phase sequence, are checked by using either synchronizing lamps or a synchroscope. There are a number of ways in which synchronizing lamps may be connected, but the most satisfactory arrangement is the TWO-BRIGHT ONE-DARK method. This connective arrangement is shown in figure 12-16. Note that the lamps are connected directly between the incoming generator's output and the buses. In this way, the two a-c sources may be synchronized before the incoming generator's main power contactor is closed. At the instant the two generators are to be paralleled L_2 and L_3 will glow with maximum brilliance and L_1 will be dark.

Assume that the incoming generator is far out of synchronism—lagging. All three lamps will appear to glow steadily, because the frequency of the voltage across them is the DIFFERENCE in the frequencies of the two generators, and thus is too high for individual alterations to be observed. As the lagging generator is accelerated, however, the lamp (differential) frequency decreases until their light flickers visibly. Their flickering will have a rotating sequence, if connections are correct, and will indicate which generator is faster.

At a point approaching synchronism, lamp L_1 will be dark because it is connected between like phases. That is, the two phase C voltages will be so nearly synchronized that their differential voltage across L_1 will be insufficient to make it glow visibly. However, this differential may still be of sufficient magnitude to damage the generators should they be connected at this time. The reason for cross-connecting L_2 and L_3 is now indicated. Under perfectly synchronized conditions, the phase voltages across L_2 and L_3 are both 120° apart, because of their cross-connec-

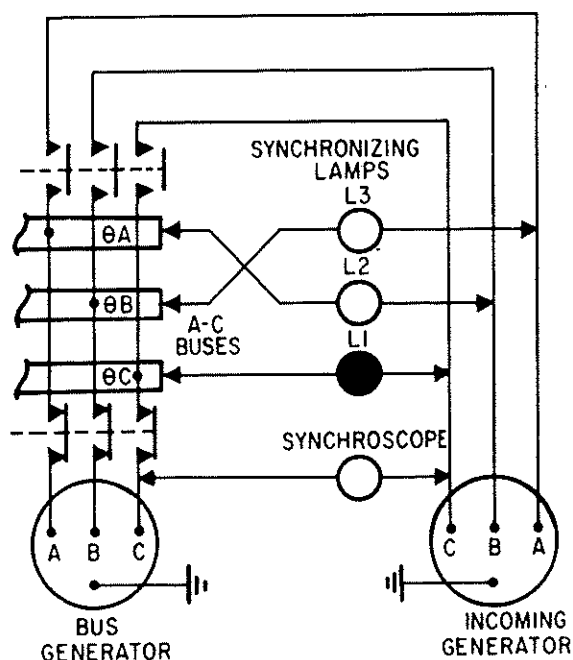


Figure 12-16.—Synchronizing lamp connection for TWO-BRIGHT ONE-DARK method.

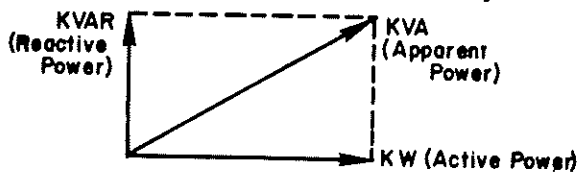
tion, and both glow with equal brilliance. However, if the generators are not in complete synchronism, but only very near it, one of the bright lamps would be increasing in voltage as the other was decreasing. This action would cause a visible difference in the brilliance of L_2 and L_3 . Thus, by adjusting the incoming generator's frequency so that no visible difference of brilliance exists between L_2 and L_3 , the exact point of synchronism can be approached very closely before paralleling the incoming generator with the generator on the bus.

When the lamps have been used to get the generators as nearly synchronized as is visibly possible, the synchroscope is used to make the final FINE adjustment to the incoming generator's frequency. A synchroscope is a highly sensitive instrument used to detect a difference in frequency between two a-c sources.

Transfer of Load between AC generators

An AC generator supplies power to a system in the form of voltage and amperage. The power known as apparent power is the product of the voltage and amperages supplied to the system and is measured in kilo-volt-amperes (kva).

The efficiency of the electrical system, that is, its ability to use this power is designated by the systems power factor. This determines how much of the apparent power is used to do work (active power kw) and how much is used to supply the field of the inductors and charge the capacitors (non-work or reactive power kvar). The apparent power is the algebraic sum of the active power and the reactive power supplied to the system.

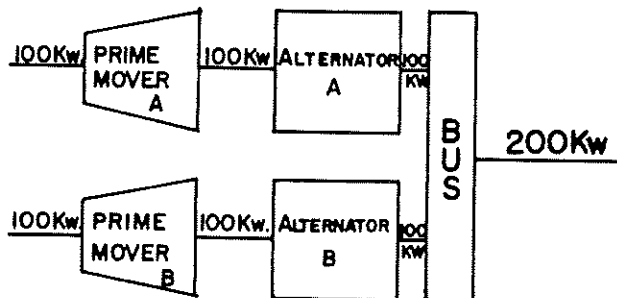


When two alternators are paralleled the total load (both active and reactive) supplied should be balanced between the two alternators.

Transfer of Active Power

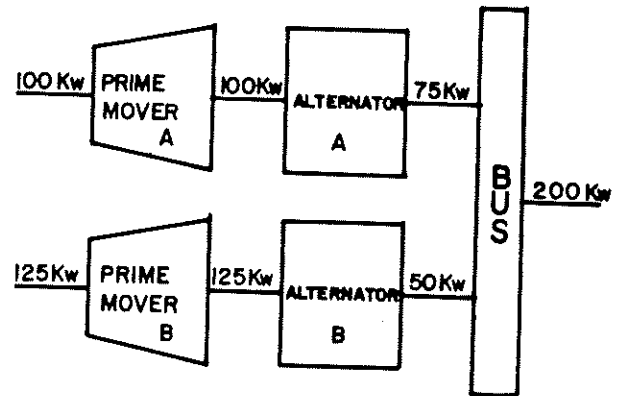
Transfer of the active power (kw) between alternators operating in parallel is accomplished by adjustment of their prime movers governor controls. The generator that is to receive more load must have more energy admitted to its prime mover while the machine that is to lose some of its load must have less energy admitted to its prime mover.

Assume for example two generators operating in parallel and supplying a common bus load of 200 kw balanced so that each generator is supplying 100 kw to the load. The system is balanced and in equilibrium, that is, the energy input to the prime movers is equal to the energy supplied to the load. Losses are considered to be negligible for the purpose of the example.

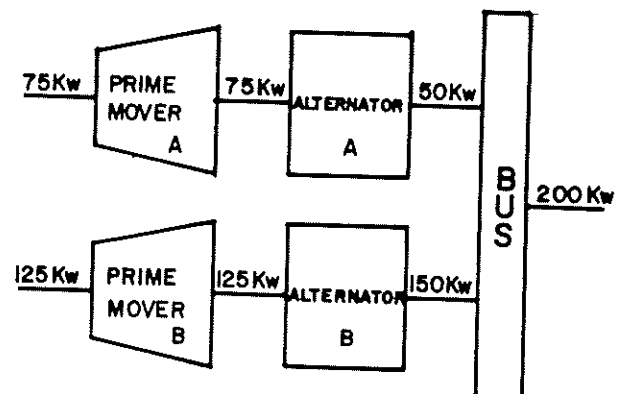


INITIAL CONDITION

To transfer 50 kw from alternator A to alternator B, move the governor control switch of alternator B to the raise position and hold it there until its watt-meter indicates that one-half of the load (25 kw) to be shifted has been transferred. To finish the transfer of load, turn the governor control switch of alternator A to the lower position and hold it there until the remaining half of the load to be shifted (25 kw) has been transferred. During the transition period, when more energy was admitted to the prime mover of machine B, the energy balance of the system was disturbed; more energy was fed into the system than was going out which resulted in an increase in the system speed and frequency. Prime mover B increased its speed because of the direct increase in the energy input. Prime mover A increased its speed because of a reduction of its load. Since one machine cannot run at a greater electrical speed than the other, if one increases in speed so must the other.



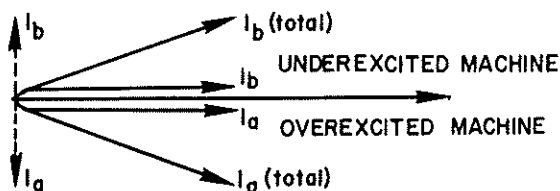
TRANSITION PERIOD



TRANSFERRED CONDITION

Transfer of Reactive Power (kvar)

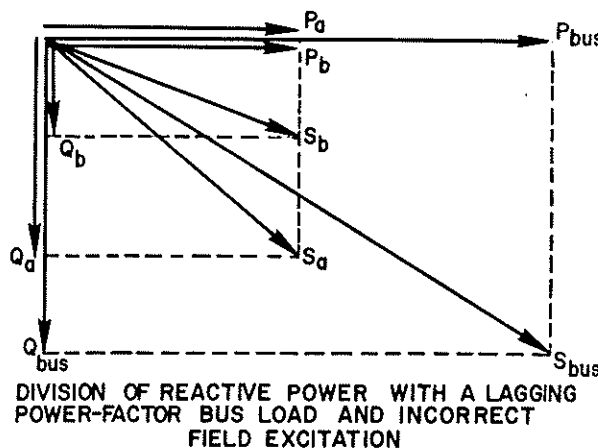
The transfer of active power (kw) between two alternators operating in parallel results in a voltage differential between the two alternators. The alternator that lost some kilowatts has its internal voltage increased because of the lessened voltage drops within its armature, due to the reduction in the armature current flow; hence the machine is over excited for the lower load. The alternator that accepted additional kilowatts has its internal voltage decreased because of the increased voltage drops within its armature, hence the machine is said to be underexcited for its increased load. If the load on the bus is operating at unity power factor, the over excited machine will feed current into the underexcited machine, causing a lagging current in the former and a leading current in the latter. This cross current between the machines is purely reactive and is illustrated in the following phasor diagram. Al-



CROSS CURRENTS BETWEEN MACHINES FOR A UNITY POWER FACTOR BUS LOAD

though the cross current between the machines does not appear at the load, it is undesirable and should be eliminated, since it increases the losses. The cross current between machines is in effect an interchange of reactive power, similar to that which occurs between a capacitor and an inductor in a parallel circuit.

If, however, the power of the bus is lagging, the transfer of active power will result in a disproportionate division of reactive power between the alternators. This is illustrated in the following phasor diagram where each alternator is carrying an equal share of the active load (kw).



The resultant voltage differential between the machines caused the now overexcited machine A to supply more kvar than the now underexcited machine B.

The balancing of reactive power (kvar) between the alternators must be accomplished by adjusting the field excitation of each alternator. The field rheostat of the underexcited machine should be turned to the "raise voltage" direction and that of the overexcited machine in the "lower voltage" direction until the kvarmeter indication or the power factor meter indication is the same for each alternator. The division of the reactive power may also be determined by observing the generator ammeters. The d-c field serving the generator ammeters. The a-c field excitation of the underexcited machine should be gradually increased and that of the overexcited machine gradually decreased until the a-c ammeter readings are both the same.

The adjustment of power factor when accomplished by increasing only the generated emf of the machine that accepted load results in an increase in bus voltage. To correct the reactive load balance without changing the bus voltage requires the excitation of each machine to be simultaneously changed until the desired voltage is obtained.

Transformers

A transformer is a device that has no moving parts and that transfers energy from one circuit to another by electromagnetic induction. The energy is always transferred without a change in frequency, but usually with changes in voltage

and current. A step-up transformer receives electrical energy at one voltage and delivers it at a higher voltage. Conversely, a stepdown transformer receives energy at one voltage and delivers it at a lower voltage. Transformers

require little care and maintenance because of their simple, rugged, and durable construction. The efficiency of transformers is high. Because of this, transformers are responsible for the more extensive use of alternating current than direct current. The conventional constant-potential transformer is designed to operate with the primary connected across a constant-potential source and to provide a secondary voltage that is substantially constant from no load to full load.

Various types of small single-phase transformers are used as shipboard equipment. In many installations, transformers are used on switchboards to stepdown the voltage for indicating lights. Low-voltage transformers are included in some motor control panels to supply control circuits or to operate overload relays. Other common uses include low-voltage supply for gunfiring circuits, special signal lights, and high-voltage ignition circuits for automatic oil burners.

Instrument transformers include POTENTIAL, or VOLTAGE, TRANSFORMERS and CURRENT TRANSFORMERS. Instrument transformers are commonly used with a-c instruments when high voltages or large currents are to be measured.

Electronic circuits and devices employ many types of transformers to provide necessary voltages for proper electron-tube operation, inter-stage coupling, signal amplification, and so forth. The physical construction of these transformers differs widely.

The POWER-SUPPLY TRANSFORMER used in electronic circuits is a single-phase constant-potential transformer with one or more secondary windings, or a single secondary with several tap connections. These transformers have a low volt-ampere capacity and are less efficient than large constant-potential power transformers. Most power-supply transformers for electronic equipment aboard ship are designed to operate at a frequency of 50 to 60 cycles per second. Aircraft power-supply transformers are designed for a frequency of 400 cycles per second. The higher frequencies permit a saving in size and weight of transformers and associated equipment.

CONSTRUCTION

The typical transformer has two windings insulated electrically from each other. These

windings are wound on a common magnetic circuit made of laminated sheet steel. The principal parts are: (1) The CORE, which provides a circuit of low reluctance for the magnetic flux; (2) the PRIMARY WINDING, which receives the energy from the a-c source; (3) the SECONDARY WINDING, which receives the energy by mutual induction from the primary and delivers it to the load, and (4) the ENCLOSURE.

When a transformer is used to step up the voltage, the low-voltage winding is the primary. Conversely, when a transformer is used to step down the voltage, the high-voltage winding is the primary. The primary is always connected to the source of the power; the secondary is always connected to the load. It is common practice to refer to the windings as the primary and secondary rather than the high-voltage and low-voltage windings.

The principal types of transformer construction are the core type and the shell type, as illustrated respectively in figure 12-17 (A) and (B). The cores are built of thin stampings of silicon steel. Eddy currents, generated in the core by the alternating flux as it cuts through the iron, are minimized by using thin laminations and by insulating adjacent laminations with insulating varnish. Hysteresis losses, caused by the friction developed between magnetic particles as they are rotated through each cycle of magnetization, are minimized by using a special grade of heat-treated grain-oriented silicon-steel laminations.

In the core-type transformer, the copper windings surround the laminated iron core. In the shell-type transformer the iron core surrounds the copper windings. Distribution transformers are generally of the core type; whereas some of the largest power transformers are of the shell type.

If the windings of a core-type transformer were placed on separate legs of the core, a relatively large amount of the flux produced by the primary winding would fail to link the secondary winding and a large leakage flux would result. The effect of the leakage flux would be to increase the leakage reactance drop, IX_L , in both windings. To reduce the leakage flux and reactance drop, the windings are subdivided and half of each winding is placed on each leg of the core. The windings may be cylindrical in form and placed one inside the other with the necessary insulation, as shown in figure 12-17 (A). The low-voltage winding is placed with a large part

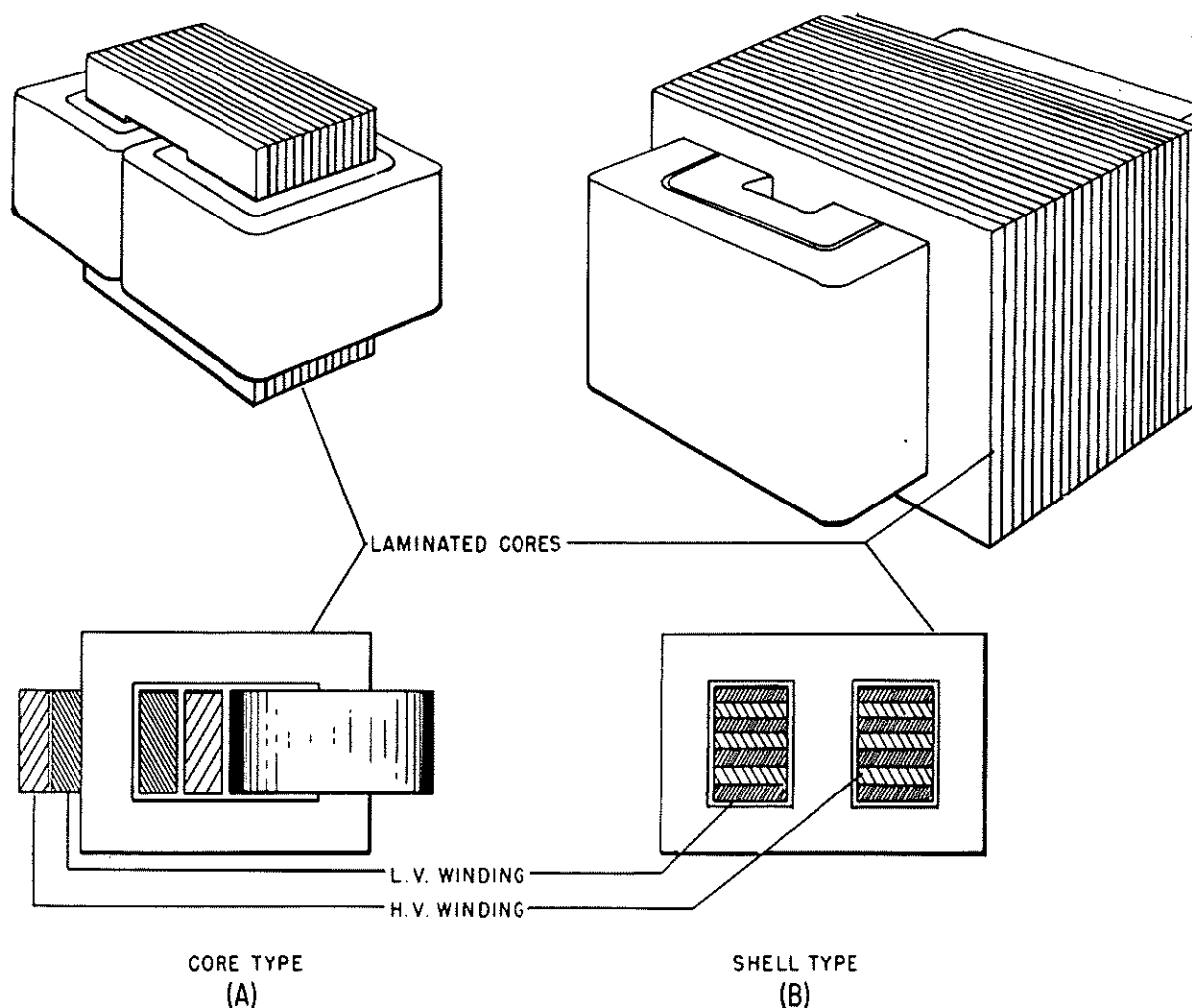


Figure 12-17.—Types of transformer construction.

of its surface area next to the core, and the high-voltage winding is placed outside the low-voltage winding in order to reduce the insulation requirements of the two windings. If the high-voltage winding were placed next to the core, two layers of high-voltage insulation would be required, one next to the core and the other between the two windings.

In another method, the windings are built up in thin flat sections called pancake coils. These pancake coils are sandwiched together, with the required insulation between them, as shown in figure 12-17 (B).

The complete core and coil assembly (fig. 12-18 (A)) is placed in a steel tank. In commercial transformers the complete assembly is usu-

ally immersed in a special mineral oil to provide a means of insulation and cooling. No oil is used in the transformer enclosures on naval vessels. Transformer banks installed in these vessels normally consist of single-phase air-cooled transformers mounted in drip-proof enclosures as shown in figure 12-18 (B).

Transformers are built in both single-phase and polyphase units. A 3-phase transformer consists of separate insulated windings for the different phases, wound on a 3-legged core capable of establishing three magnetic fluxes displaced 120° in time phase. Three-phase transformers are not installed aboard ship because the loss of a composite unit would result in an interruption to service. To insure continuity of

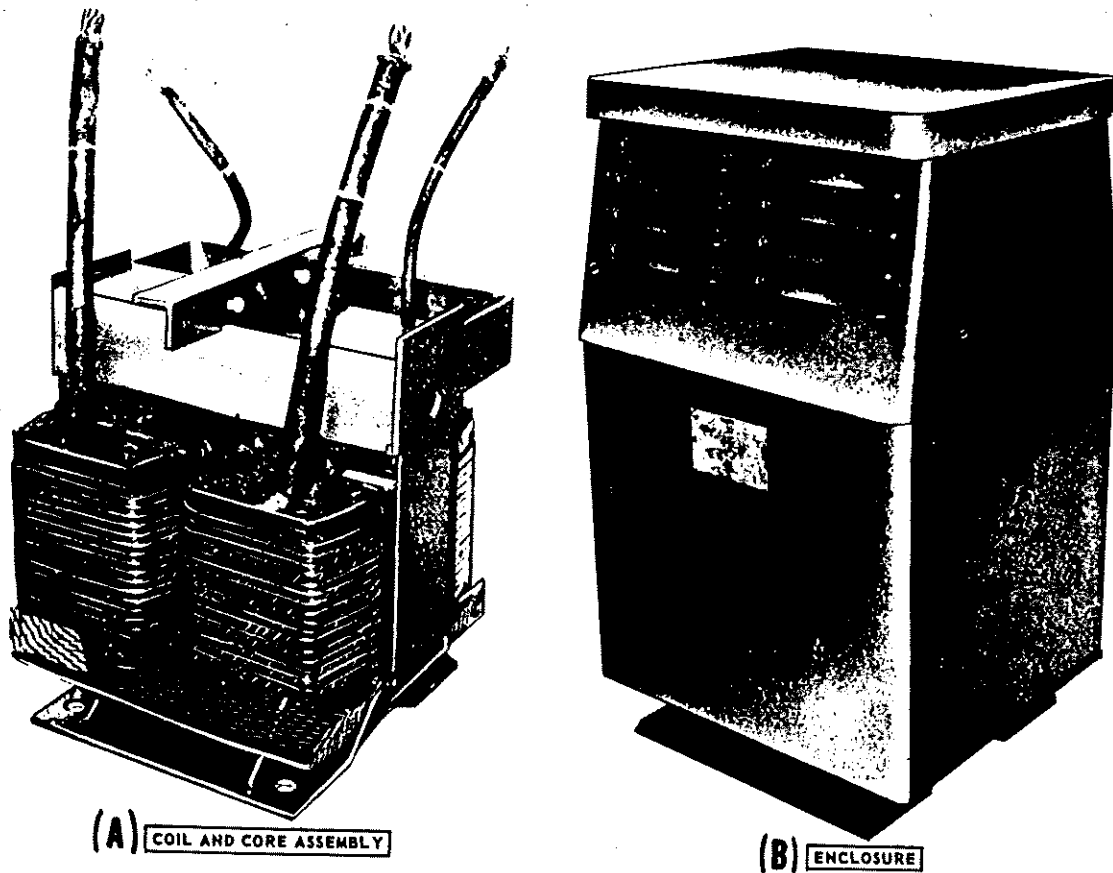


Figure 12-18.—Single-phase transformer for shipboard use.

service, three separate single-phase delta-connected transformers are installed to supply low-voltage service. If one transformer is damaged in such a system, it can be removed and the remaining two transformers can be operated in the open delta to supply the 3-phase service, but at a reduction in the original load capacity of the transformer bank. Because of the saving in space and weight, 3-phase transformers are often used in high-power airborne radar sets, and these are sometimes immersed in oil.

VOLTAGE AND CURRENT RELATIONS

The operation of the transformer is based on the principle that electrical energy can be transferred efficiently by mutual induction from one winding to another. When the primary winding is energized from an a-c source, an alternating magnetic flux is established in the transformer core. This flux links the turns of both primary

and secondary, thereby inducing voltages in them. Because the same flux cuts both windings, the same voltage is induced in each turn of both windings. Hence, the total induced voltage in each winding is proportional to the number of turns in that winding. That is,

$$\frac{E_1}{E_2} = \frac{N_1}{N_2}$$

where E_1 and E_2 are the induced voltages in the primary and secondary windings, respectively, and N_1 and N_2 are the number of turns in the primary and secondary windings, respectively. In ordinary transformers the induced primary voltage is almost equal to the applied primary voltage; hence, the applied primary voltage and the secondary induced voltage are approximately proportional to the respective number of turns in the two windings.

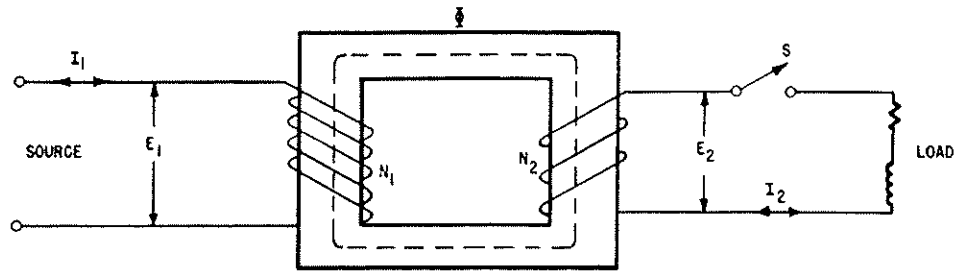


Figure 12-19.—Constant-potential transformer.

A constant-potential single-phase transformer is represented by the schematic diagram in figure 12-19 (A). For simplicity, the primary winding is shown as being on one leg of the core and the secondary winding on the other leg.

The copper loss of a transformer varies as the square of the load current; whereas the core loss depends on the terminal voltage applied to the primary and on the frequency of operation. The core loss of a constant-potential transformer is constant from no load to full load because the frequency is constant and the effective values of the applied voltage, exciting current, and flux density are constant.

If the load supplied by a transformer has unity power factor, the kilowatt (true power) output is the same as the kilovolt-ampere (apparent power) output. If the load has a lagging power factor, the kilowatt output is proportionally less than the kilovolt-ampere output. For example, a transformer having a full-load rating of 100 kv.-a. can supply a 100-kw. load at unity power factor, but only an 80-kw. load at a lagging power factor of 80 percent.

Navy shipboard transformers are generally rated in terms of the kv.-a. load that they can safely carry continuously without exceeding a temperature rise of 80° C. when maintaining rated secondary voltage at rated frequency and when operating with an ambient (surrounding atmosphere) temperature of 40° C. The actual temperature RISE of any part of the transformer is the difference between the total temperature of that part and the temperature of the surrounding air.

It is possible to operate transformers on a higher frequency than that for which they are

designed, but it is not permissible to operate them at more than 10 percent below their rated frequency, because of the resulting overheating. The exciting current in the primary varies directly with the applied voltage and, like any impedance containing inductive reactance, the exciting current varies inversely with the frequency. Thus, at reduced frequency, the exciting current becomes excessively large and the accompanying heating may damage the insulation and the windings.

EFFICIENCY

The efficiency of a transformer is the ratio of the output power at the secondary terminals to the input power at the primary terminals. It is also equal to the ratio of the output to the output plus losses. That is,

$$\text{efficiency} = \frac{\text{output}}{\text{input}} = \frac{\text{output}}{\text{output} + \text{copper loss} + \text{core loss}}$$

The ordinary power transformer has an efficiency of 97 to 99 percent. The losses are due to the copper losses in both windings and the hysteresis and eddy-current losses in the iron core.

The copper losses vary as the square of the current in the windings and as the winding resistance. In the transformer being considered, if the primary has 1,100 turns of number 23 copper wire, having a length of 1,320 feet, the resistance of the primary winding is 26.9 ohms.

If the load current in the primary is 0.5 ampere, the primary copper loss is $(0.5)^2 \times 26.9 = 6.725$

watts. Similarly, if the secondary winding contains 110 turns of number 13 copper wire, having a length of approximately 132 feet, the secondary resistance will be 0.269 ohm. The secondary copper loss is $I_2^2 R_2$, or $(5)^2 \times 0.269 = 6.725$ watts, and the total copper loss is $6.725 \times 2 = 13.45$ watts.

The core losses, consisting of the hysteresis and eddy-current losses, caused by the alternating magnetic flux in the core are approximately constant from no load to full load, with rated voltage applied to the primary.

In the transformer of figure 12-19 (A), if the core loss is 10.6 watts and the copper loss is 13.4 watts, the efficiency is

$$\frac{\text{output}}{\text{output} + \text{copper loss} + \text{core loss}} = \frac{476}{476 + 13.4 + 10.6} = \frac{476}{500} = 0.952,$$

or 95.2 percent. The rating of the transformer is

$$\frac{E_1 I_1}{1,000} = \frac{1,100 \times 0.5}{1,000} = 0.55 \text{ kv.-a.}$$

The efficiency of this transformer is relatively low because it is a small transformer and the losses are disproportionately large.

SINGLE-PHASE CONNECTIONS

Single-phase distribution transformers usually have their windings divided into two or more sections, as shown in figure 12-20. When the two secondary windings are connected in series (fig. 12-20 (A)), their voltages add. In figure 12-20 (B), the two secondary windings are connected in parallel, and their currents add. For example, if each secondary winding is rated at 115 volts and 100 amperes, the series-connection output rating will be 230 volts at 100 amperes, or 23 kv.-a.; the parallel-connection output rating will be 115 volts at 200 amperes, or 23 kv.-a.

In the series connection, care must be taken to connect the coils so that their voltages add. The proper arrangement is indicated in the figure. A trace made through the secondary circuits from X_1 to X_4 is in the same direction as that of the arrows representing the maximum positive voltages.

In the parallel connection, care must be taken to connect the coils so that their voltages are in opposition. The correct connection is indicated in the figure. The direction of a trace made through the secondary windings from X_1 to X_2 to X_4 to X_3 and returning to X_1 is the same as that of the arrow in the right-hand winding. This condition indicates that the secondary voltages have their positive maximum values in directions opposite to each other in the closed circuit,

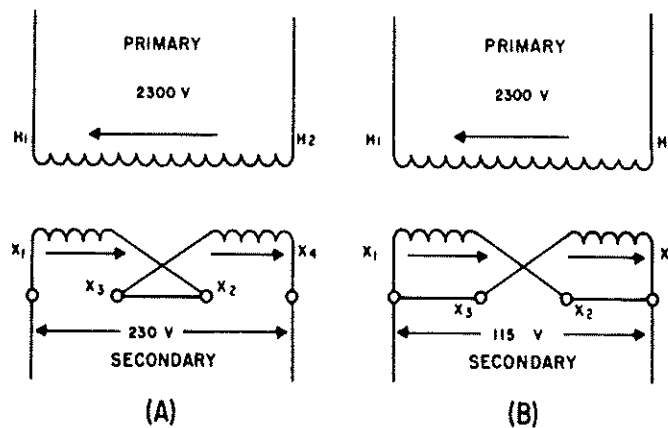


Figure 12-20.—Single-phase transformer secondary connections.

which is formed by paralleling the two secondary windings. Thus, no circulating current will flow in these windings on no load. If either winding were reversed, a short-circuit current would flow in the secondary, and this would cause the primary to draw a short-circuit current from the source. This action would, of course, damage the transformer as well as the source.

THREE-PHASE CONNECTIONS

Power may be supplied through 3-phase circuits containing transformers in which the primaries and secondaries are connected in various wye and delta combinations. For example, three single-phase transformers may supply 3-phase power with four possible combinations of their primaries and secondaries. These connections are: (1) primaries in delta and secondaries in delta, (2) primaries in wye and secondaries in wye, (3) primaries in wye and secondaries in delta, (4) primaries in delta and secondaries in wye.

Delta and wye connections were described earlier in this chapter under the subject "Three-Phase Generators," and the relations between line and phase voltages and currents were also described. These relations apply to transformers as well as to a-c generators.

If the primaries of three single-phase transformers are properly connected (either in wye or delta) to a 3-phase source, the secondaries may be connected in delta, as shown in figure 12-21. A topographic vector diagram of the 3-phase secondary voltages is shown in figure

12-21 (A). The vector sum of these three voltages is zero. This may be seen by combining any two vectors, for example, E_A and E_B , and noting that their sum is equal and opposite to the 3rd vector, E_C . A voltmeter inserted within the delta will indicate zero voltage, as shown in figure 12-21 (B), when the windings are connected properly.

Assuming all three transformers have the same polarity, the delta connection consists in connecting the X_2 lead of winding A to the X_1 lead of B , the X_2 lead of B to X_1 of C , and the X_2 lead of C to X_1 of A . If any one of the three windings is reversed with respect to the other two windings, the total voltage within the delta will equal twice the value of one phase; and if the delta is closed on itself, the resulting current will be of short-circuit magnitude, with resulting damage to the transformer windings and cores. The delta should never be closed until a test is first made to determine that the voltage within the delta is zero or nearly zero. This may be done with a voltmeter, fuse wire, or test lamp. In the figure, when the voltmeter is inserted between the X_2 lead of A and the X_1 lead of B , the delta circuit is completed through the voltmeter, and the indication should be approximately zero. Then the delta is completed by connecting the X_2 lead of A to the X_1 lead of B .

If the three secondaries of an energized transformer bank are properly connected in delta

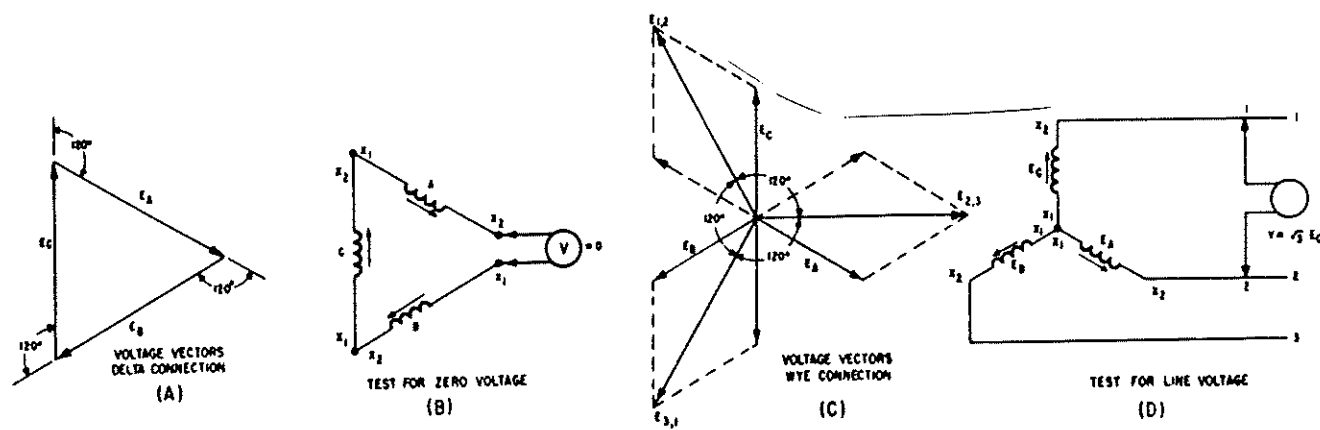


Figure 12-21.—Delta-connected transformer secondaries.

and are supplying a balanced 3-phase load, the line current will be equal to 1.73 times the phase current. If the rated current of a phase (winding) is 100 amperes, the rated line current will be 173 amperes. If the rated voltage of a phase is 120 volts, the voltage between any two line wires will be 120 volts.

The three secondaries of the transformer bank may be reconnected in wye in order to increase the output voltage. The voltage vectors are shown in figure 12-21 (C). If the phase voltage is 120 volts, the line voltage will be $1.73 \times 120 = 208$ volts. The line voltages are represented by vectors, $E_{1,2}$, $E_{2,3}$, and $E_{3,1}$. A voltmeter test for the line voltage is represented in figure 12-21. (D). If the three transformers have the same polarity, the proper connections for a wye-connected secondary bank are indicated in the figure. The X_1 leads are connected to form a common or neutral connection and the X_2 leads of the three secondaries are brought out to the line leads. If the connections of any one winding are reversed, the voltages between the 3 line wires will become unbalanced, and the loads will not receive their proper magnitude of load cur-

rent. Also the phase angle between the line currents will be changed, and they will no longer be 120° out of phase with each other. Therefore, it is important to properly connect the transformer secondaries in order to preserve the symmetry of the line voltages and currents.

Transformer installations aboard naval vessels usually consist of 450/117-volt delta-connected banks to supply the general lighting circuits and service for the interior-communications and fire control circuits. Some ships also include 450/230-volt delta-connected banks to supply the galley equipment. Power is distributed over an ungrounded 3-wire, 3-phase, 450-volt system.

Three single-phase transformers with both primary and secondary windings delta connected are shown in figure 12-23. The H_1 lead of one phase is always connected to the H_2 lead of an adjacent phase, the X_1 lead is connected to the X_2 terminal of the corresponding adjacent phase, and so on; and the line connections are made at these junctions. This arrangement is based on the assumption that the three transformers have the same polarity.

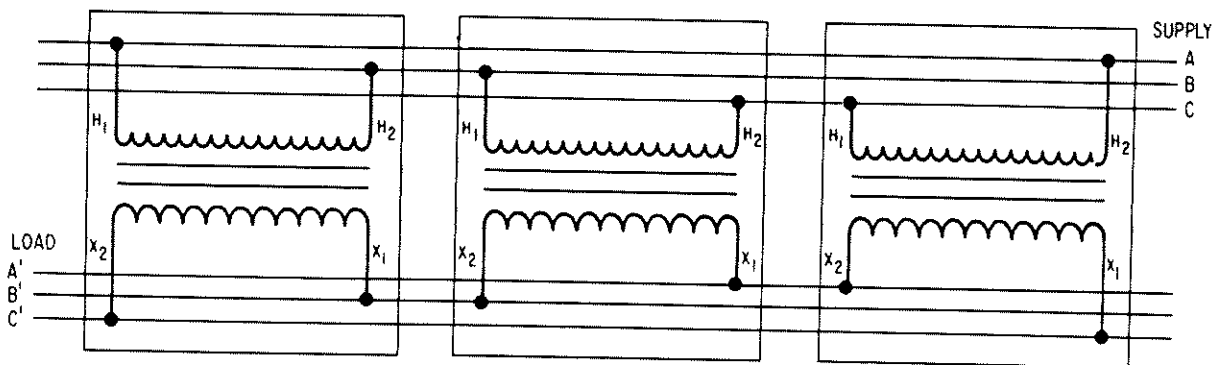


Figure 12-22. —Delta-delta transformer connections.

An open-delta connection results when any one of the three transformers is removed from the delta-connected transformer bank without disturbing the 3-wire 3-phase connections to the remaining two transformers. These transformers will maintain the correct voltage and phase relations on the secondary to supply a balanced 3-phase load. An open-delta connection is shown in figure 12-23. The 3-phase source supplies the primaries of the two transformers, and the secondaries supply a 3-phase voltage to the load.

The LINE CURRENT is equal to the transformer PHASE CURRENT in the open-delta connection. In the closed-delta connection, the transformer phase current, $I_{\text{phase}} = \frac{I_{\text{line}}}{\sqrt{3}}$. Thus, when one transformer is removed from a delta-connected bank of three transformers, the remaining two transformers will carry a current equal to $\sqrt{3} I_{\text{phase}}$. This value amounts to an overload current on each transformer of 1.73 times the rated current, or an overload of 73.2 percent.

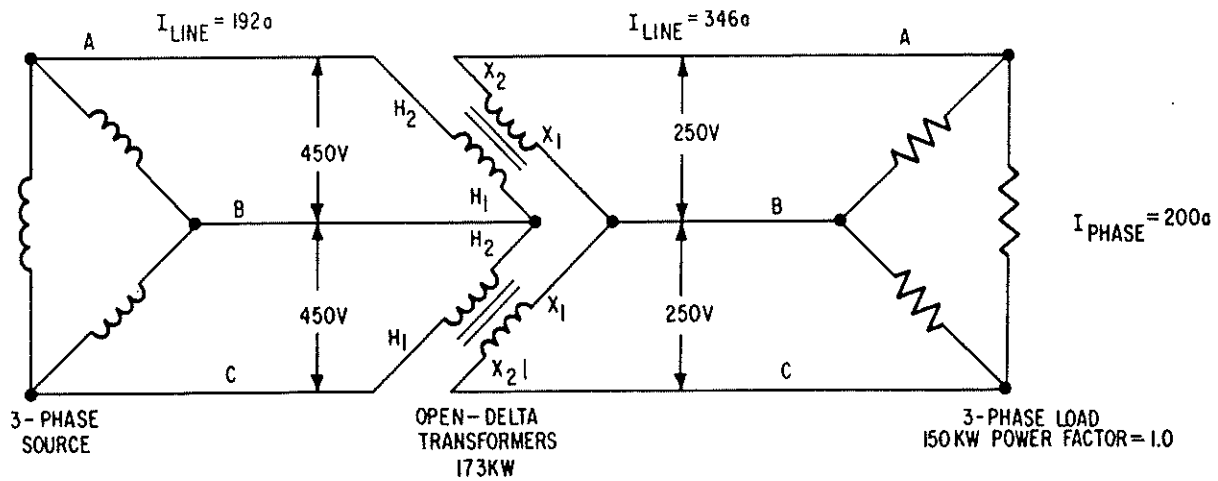


Figure 12-23.—Open-delta transformer connection.

Thus, in an open-delta connection, the line current must be reduced so as not to exceed the rated current of the individual transformers if they are not to be overloaded. The open-delta connection therefore results in a reduction in system capacity. The full-load capacity in a delta connection at unity power factor is

$$P_{\Delta} = 3I_{\text{phase}} E_{\text{phase}} = \sqrt{3} E_{\text{line}} I_{\text{line}}$$

In an open-delta connection, the line current is limited to the rated phase current of $\frac{I_{\text{line}}}{\sqrt{3}}$, and the full-load capacity of the open-delta, or V-connected, system is

$$P_v = \sqrt{3} E_{\text{line}} \frac{I_{\text{line}}}{\sqrt{3}} = E_{\text{line}} I_{\text{line}}$$

The ratio of the load that can be carried by two transformers connected in open delta to the load that can be carried by three transformers in closed delta is

$$\frac{P_v}{P_{\Delta}} = \frac{E_{\text{line}} I_{\text{line}}}{\sqrt{3} E_{\text{line}} I_{\text{line}}} = \frac{1}{\sqrt{3}} = 0.577, \text{ or } 57.7 \text{ percent}$$

of the closed-delta rating.

For example, a 150-kw. 3-phase balanced load operating at unity power factor is supplied at 250 volts. The rating of each of three transformers in closed delta is $\frac{150}{3} = 50$ kw., and the phase current is $\frac{50,000}{250} = 200$ amperes. The line current is $200\sqrt{3} = 346$ amperes. If one transformer is removed from the bank, the remaining

two transformers would be overloaded $346 - 200 = 146$ amperes, or $\frac{146}{200} \times 100 = 73$ percent. To prevent overload on the remaining two transformers, the line current must be reduced from 346 amperes to 200 amperes and the total load reduced to

$$\frac{\sqrt{3} \times 250 \times 200}{1,000} = 86.6 \text{ kw.},$$

or

$$\frac{86.6}{150} \times 100 = 57.7 \text{ percent}$$

of the original load.

The rating of each transformer in open delta necessary to supply the original 150-kw. load is

$$\frac{E_{\text{phase}} I_{\text{phase}}}{1,000}, \text{ or } \frac{250 \times 346}{1,000} = 86.6 \text{ kw.}, \text{ and two}$$

transformers require a total rating of $2 \times 86.6 = 173.2$ kw., compared with 150 kw. for three transformers in closed delta. The required increase in transformer capacity is $173.2 - 150 = 23.2$ kw., or $\frac{23.2}{150} \times 100 = 15.5$ percent, when two transformers are used in open delta to supply the same load as three 50-kw. transformers in closed delta.

Three single-phase transformers with both primary and secondary windings wye connected are shown in figure 12-24. Only 57.7 percent of

the line voltage ($\frac{E_{\text{line}}}{\sqrt{3}}$) is impressed across each

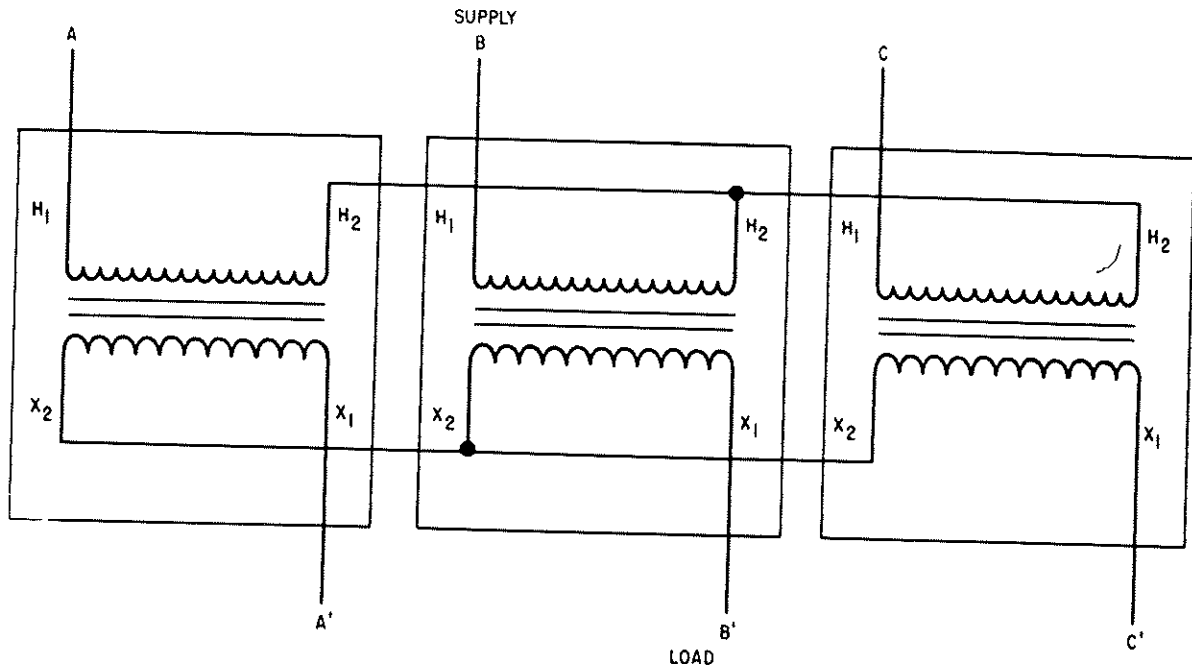


Figure 12-24.—Wye-wye transformer connections.

winding, but full-line current flows in each transformer winding. Although the wye-wye connection is never used aboard ship, it is frequently used in Navy shore installations.

Three single-phase transformers delta connected to the primary circuit and wye connected to the secondary circuit are shown in figure 12-25. This connection provides 4-wire, 3-phase

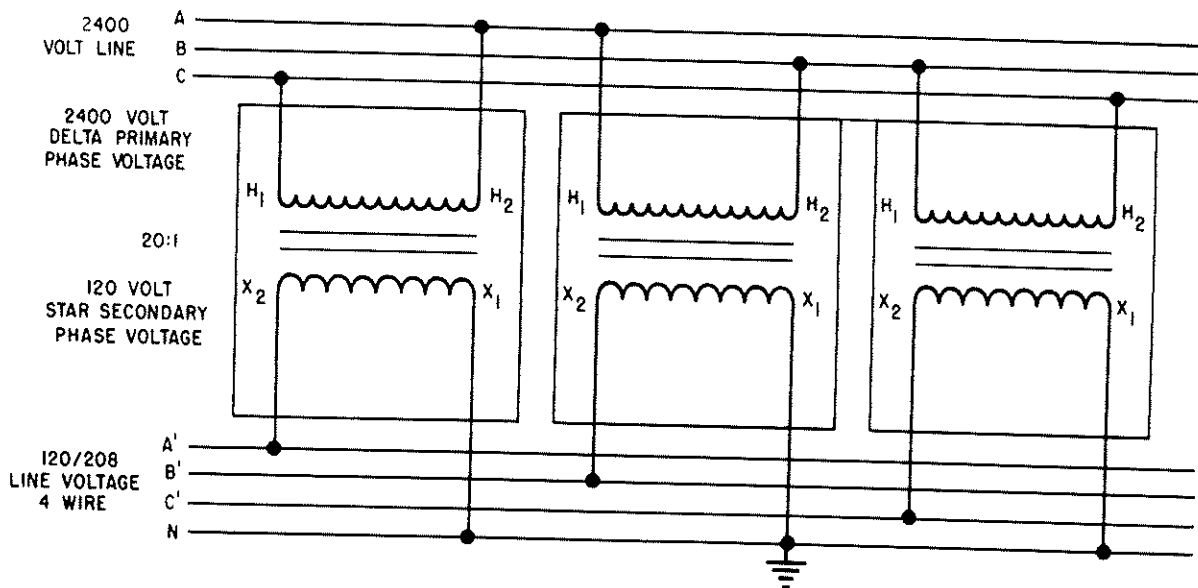


Figure 12-25.—Delta-wye transformer connections.

service with 208 volts between line wires $A'B'C'$, and $\frac{208}{\sqrt{3}}$, or 120 volts, between each line wire and neutral N . The wye-connected secondary is desirable in shore installations when a large number of single-phase loads are to be supplied from a 3-phase transformer bank. The neutral, or grounded, wire is brought out from the mid-point of the wye connection, permitting the single-phase loads to be distributed evenly across the three phases. At the same time, 3-phase loads can be connected directly across the line wires. The single-phase loads have a voltage rating of 120 volts, and the 3-phase loads are rated at 208 volts. This connection is often used in high-voltage plate-supply transformers in aircraft radar power supplies. The phase voltage is $\frac{1}{1.73}$, or 0.577 of the line voltage.

Three single-phase transformers with wye-connected primaries and delta-connected secondaries are shown in figure 12-26. This arrangement is used for stepping down the voltage from approximately 4,000 volts between line wires on the primary side to either 115 volts or 230 volts, depending upon whether the secondary windings of each transformer are connected in parallel or in series. In the figure, the two secondaries of each transformer are connected in parallel, and the secondary output voltage is 115 volts. There is an economy in transmission with the primaries in wye because the line voltage is 73 percent higher than the phase voltage, and the line current is accordingly less. Thus, the line losses are reduced and the efficiency of transmission is improved.

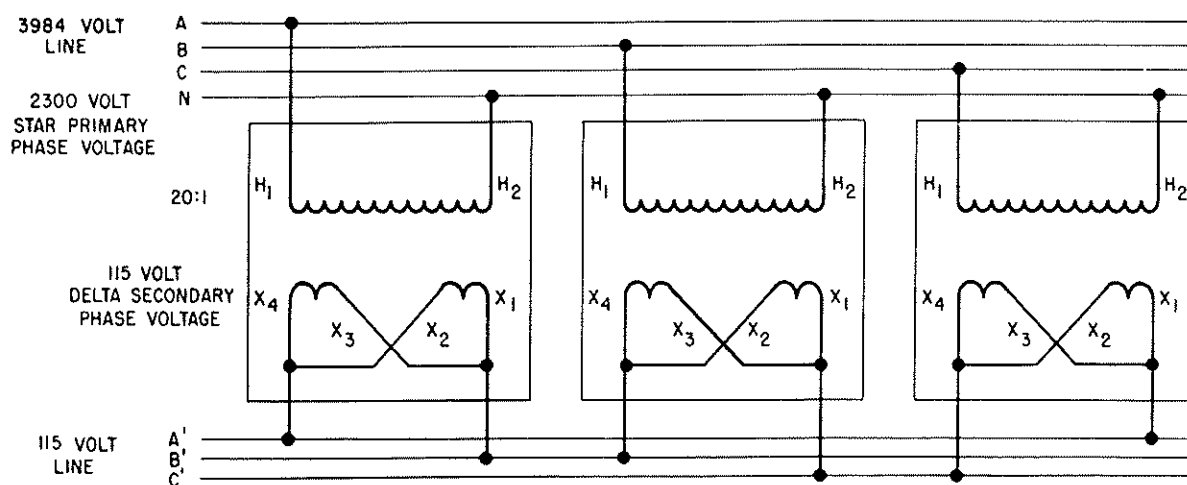


Figure 12-26.—Wye-delta transformer connections.

QUIZ

1. An a-c armature is always the
 - a. rotating part of the generator
 - b. stationary part of the generator
 - c. conductors into which voltage is induced
 - d. conductors through which d-c exciter current flows
2. The armature windings of a 2-phase a-c generator are physically placed so that the induced voltages are out of phase by
 - a. 30°
 - b. 60°
 - c. 90°
 - d. 120°
3. When connecting a 3-phase a-c generator for delta operation, the delta closure voltage should be
 - a. line voltage
 - b. phase voltage
 - c. approximately zero volts
 - d. less than phase voltage
4. With no load on the secondary, the current in the primary is
 - a. zero
 - b. limited only by the resistance of the winding
 - c. determined by c.e.m.f. of secondary
 - d. determined by c.e.m.f. of primary
5. The a-c field is always the
 - a. rotating part of the generator
 - b. stationary part of the generator
 - c. conductors into which voltage is induced
 - d. conductors through which d-c exciter current flows
6. The voltage induced into the armature windings is maximum when the field poles are
 - a. in the neutral plane
 - b. opposite the armature poles
 - c. between the armature poles
 - d. rotating at a high speed
7. The output frequency of an a-c generator is dependent upon the
 - a. number of poles and phases
 - b. rotor speed and phases
 - c. number of poles and the speed of the prime mover
 - d. number of poles and the rotor speed
8. The load rating of an a-c generator is determined by the
 - a. internal heat it can withstand
 - b. load it can carry continuously
 - c. load it is capable of supplying
 - d. overload it can carry for a specified time only
9. In a 2-phase 3-wire a-c generator, the formula for line voltage is
 - a. $E_L = \frac{E_p}{\cos 45^\circ}$
 - b. $E_L = \frac{E_p}{\tan 45^\circ}$
 - c. $E_L = E_p \times 0.707$
 - d. $E_L = E_p \times 1.73$
10. The voltage output of an a-c generator is controlled by
 - a. regulating the speed of the prime mover
 - b. varying the d-c exciter voltage
 - c. varying the reluctance of the air gap
 - d. shorting out part of the armature windings
11. The primary reason for connecting transformers wye-wye is to
 - a. double the input voltage
 - b. double the primary current
 - c. invert the frequency
 - d. decrease line losses by high voltage with low current in the line
12. The purpose of the d-c generator is to excite the
 - a. a-c armature
 - b. a-c field
 - c. d-c armature
 - d. a-c and d-c field
13. A 3-phase wye-connected a-c generator is used to produce
 - a. high current, low voltage
 - b. low current, low voltage
 - c. low current, high voltage
 - d. high current, high voltage
14. Two types of instrument transformers are
 - a. step-up and step-down
 - b. potential and high voltage
 - c. potential and current
 - d. auto and power
15. The output of a rotating field a-c generator is taken from
 - a. sliprings and brushes
 - b. commutator bars and brushes
 - c. fixed terminals
 - d. none of the above
16. Aircraft transformers are designed for 400 c.p.s. because
 - a. of the 400-c.p.s. supply available in the aircraft
 - b. the higher frequency permits savings of size and weight
 - c. it is more stable than lower frequencies
 - d. it has a higher average current flow
17. The closure voltage of a delta-connected transformer secondary is
 - a. 0 volts
 - b. phase voltage
 - c. line voltage
 - d. line voltage x 1.73
18. The revolving field type a-c generator is most widely used because of
 - a. low armature current
 - b. improved safety features
 - c. low field current through fixed terminals
 - d. high power from armature through slip-rings

ALTERNATING-CURRENT GENERATORS AND TRANSFORMERS

19. When using an a-c generator on a 3-phase 4-wire system, the neutral wire
 - a. maintains equal current in each phase
 - b. maintains equal power in each phase
 - c. maintains equal voltage in each phase
 - d. has no current flow when the loads are unbalanced
20. The three principal parts of a transformer are its
 - a. core, primary windings, and secondary windings
 - b. primary, load, and magnetic flux
 - c. primary windings, secondary windings, and magnetic flux
 - d. mutual induction, magnetic flux, and windings
21. A-c generators are classified
 - a. as to construction
 - b. as to power output
 - c. according to type of prime mover
 - d. according to load connections
22. The principle of operation of a transformer is
 - a. electromagnetic induction
 - b. varying a conductor in a magnetic field
 - c. mutual induction
 - d. thermionic emission

CHAPTER 13

ALTERNATING-CURRENT MOTORS

Most of the power generating systems ashore and afloat produce alternating current. Thus, it follows that a great majority of the motors used throughout the Navy are designed to operate on alternating current. However, there are other advantages in the use of a-c motors besides the wide availability of a-c power. In general, a-c motors are less expensive than d-c motors. Some types of a-c motors do not employ brushes and commutators. This eliminates many problems of maintenance and wear; in addition, it eliminates the problem of dangerous sparking.

D-c motors are best suited for some uses, such as applications that require variable-speed

motors. However, in the great majority of applications, the a-c motor is best.

A-c motors are manufactured in many different sizes, shapes, and ratings, for use on an even greater number of jobs. They are designed for use with either polyphase or single-phase power systems.

This chapter cannot possibly cover all aspects of the subject of a-c motors. Consequently, it will deal mainly with the operating principles of only the two most common types—the rotating-field induction motor and the synchronous motor.

The Rotating Field

The rotating field is set up by out-of-phase currents in the stator windings. Figure 13-1 illustrates the manner in which a rotating field is produced by stationary coils, or windings, when they are supplied by a 3-phase current source. For purpose of explanation, rotation of the field is developed in the figure by "stopping" it at six selected positions, or instants. These instants are marked off at 60 degree intervals on the sine waves representing currents in the three phases A, B, and C.

At instant 1 the current in phase B is maximum positive. (Assume plus 10 amperes in this example.) Current is considered to be positive when it is flowing out from a motor terminal, and negative when it flows into a motor terminal. At the same time (instant 1) current flows into the A and C terminals at half value (minus 5 amperes each in this case). These currents combine at the neutral (common connection) to supply plus 10 amperes out through the B phase.

The resulting field at instant 1 is established downward and to the right as shown by the arrow NS. The major portion of this field is produced by the B phase (full strength at this time) and is aided by the adjacent phases A and C (half

strength). The weaker portions of the field are indicated by the letters "n" and "s". The field is a two-pole field extending across the space that would normally contain the rotor.

At instant 2 the current in phase B is reduced to half value (plus 5 amperes in this example). The current in phase C has reversed its flow from minus 5 amperes to plus 5 amperes, and the current in phase A has increased from minus 5 to minus 10 amperes.

The resulting field at instant 2 is now established upward and to the right as shown by arrow NS. The major portion of the field is produced by phase A (full strength) and the weaker portions by phases B and C (half strength).

At instant 3 the current in phase C is plus 10 amperes and the field extends vertically upward; at instant 4 the current in phase B becomes minus 10 amperes and the field extends upward and to the left; at instant 5 the current in phase A becomes plus 10 amperes and the field extends downward and to the left; at instant 6 the current in phase C is minus 10 amperes and the field extends vertically downward. Instant 7 (not shown) corresponds to instant 1 when the field again extends downward and to the right.

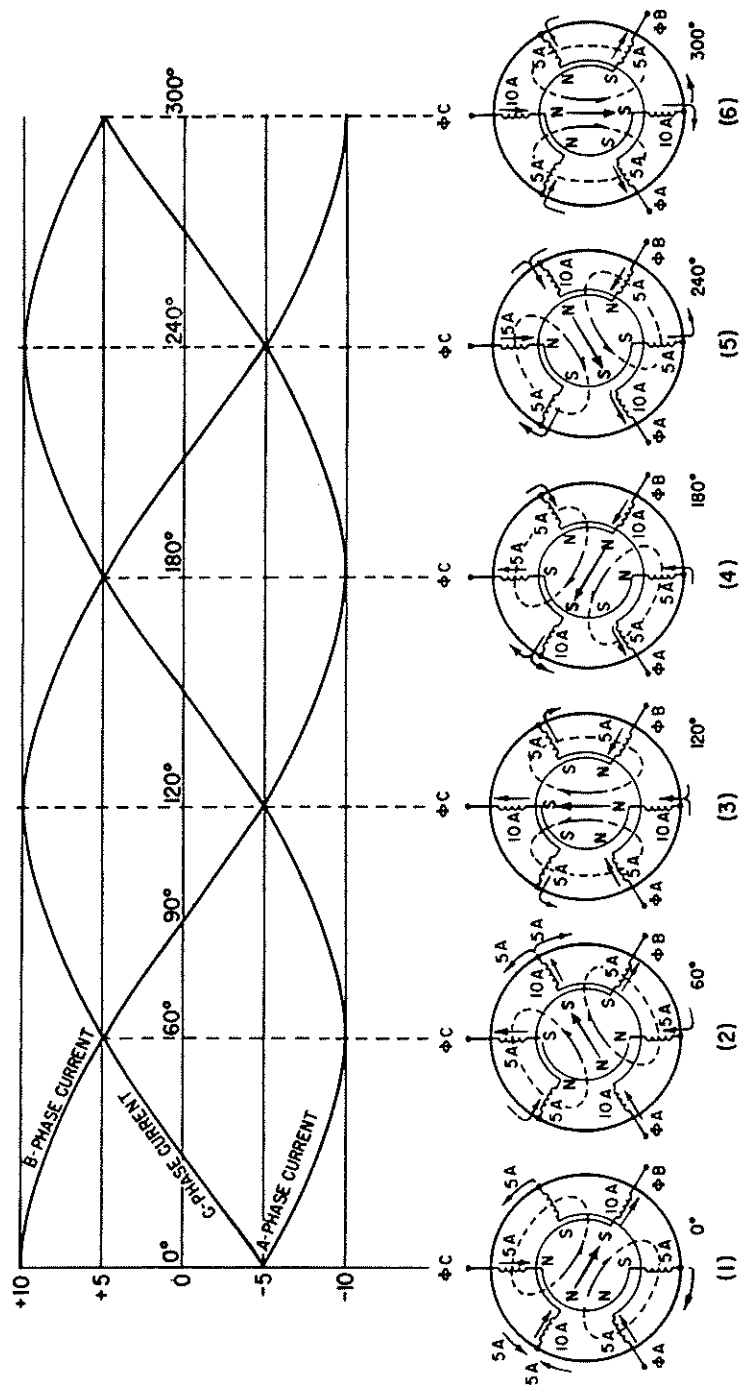


Figure 13-1.—Development of a rotating field.

Thus a full rotation of the two-pole field has been accomplished through one full cycle of 360 electrical degrees of the three-phase currents flowing in the windings.

The direction of rotation of the magnetic revolving field may be changed by interchanging any two line leads to the three motor terminals. For example, in figure 13-2 (A), if line 1 connects to phase *a*, line 2 to phase *b*, and line 3 to phase *c*, and the line currents reach their positive maximum values in the sequence 1, 2, 3, the phase sequence is *a, b, c* and the rotation is arbitrarily clockwise. If lines 1 and 2 are interchanged, the phase sequence becomes *b, a, c*, and the revolving field turns counterclockwise.

Most induction motors used by the Navy are designed to operate on single-phase power supplies, or the 3-phase supply used in the preceding discussion. The out-of-phase currents necessary to produce a rotating field are inherent in the 2-phase power supply, since 2-phase voltages are generated 90° apart. When a single-phase supply is used, it is necessary to split the power supply into two separate coil groups. The required phase difference is then generally obtained by inserting capacitance in series with one of the groups (other methods are sometimes used). This causes the single-phase or "split-phase" motor to have characteristics similar in many respects to the true 2-phase motor.

In figure 14-1, note that the sine waves of current traversed 300° through the six positions shown. Accordingly, the field rotated 300°. If the supplied current completes 60 cycles each second, the field would rotate at 60 revolutions per second (60 x 60 = 3,600 revolutions per minute). However, if the number of stator coils were doubled, producing a 4-pole field, the field will rotate only half as fast. Thus, it can be seen that the speed of the revolving field varies directly

as the frequency of the applied voltage and inversely as the number of poles.

Thus,

$$N = \frac{120f}{P}$$

where *N* is the number of revolutions that the field makes per minute, *f* the frequency of the applied voltage in cycles per second, and *P* the number of poles produced by the 3-phase winding.

The speed at which an induction motor field rotates is referred to as its SYNCHRONOUS speed, because it is synchronized to the frequency of the power supply at all times. A motor having a 2-pole 3-phase stator winding connected to a 60-cycle source has a synchronous speed (magnetic revolving field speed) of 3,600 r.p.m. A 2-pole 25-cycle motor has a synchronous speed of 1,500 r.p.m. Increasing the number of poles lowers the speed. Thus, a 4-pole 25-cycle motor has a synchronous speed of 750 r.p.m. A 12-pole 60-cycle motor has a synchronous speed of 600 r.p.m. Increasing the frequency of the line supply increases the speed with which the field revolves. Thus, if the frequency is increased from 50 to 60 cycles, and the motor has 4 poles, the speed of the field is increased from 1,500 r.p.m. to 1,800 r.p.m.

The speed of the rotating field is always independent of load changes on the motor, provided the line frequency is maintained constant. The magnetic revolving field always runs at the same speed, pole for pole, as the a-c generator supplying it. If a 2-pole 60-cycle a-c generator supplies a 2-pole motor, the motor has a synchronous speed of 3,600 r.p.m. which is the same as the speed of the a-c generator. If a 4-pole 60-cycle a-c generator runs at 1,800 r.p.m. and supplies a 4-pole 60-cycle motor, the motor has a synchronous speed of 1,800 r.p.m. If this same a-c generator supplies an 8-pole 60-cycle motor, the motor has a synchronous speed of 900 r.p.m.

Polyphase Induction Motors

The driving torque of both d-c and a-c motors is derived from the reaction of current-carrying conductors in a magnetic field. In the d-c motor, the magnetic field is stationary and the armature, with its current-carrying conductors, rotates. The current is supplied to the armature through a commutator and brushes.

In induction motors, the rotor currents are supplied by electro-magnetic induction. The sta-

tor windings contain two or more out-of-time-phase currents, which produce corresponding m.m.f.'s. These m.m.f.'s establish a rotating magnetic field across the air gap. This magnetic field rotates continuously at constant speed regardless of the load on the motor. The stator winding corresponds to the armature winding of a d-c motor or to the primary winding of a transformer. The rotor is not connected electrically to the power supply. The induction motor

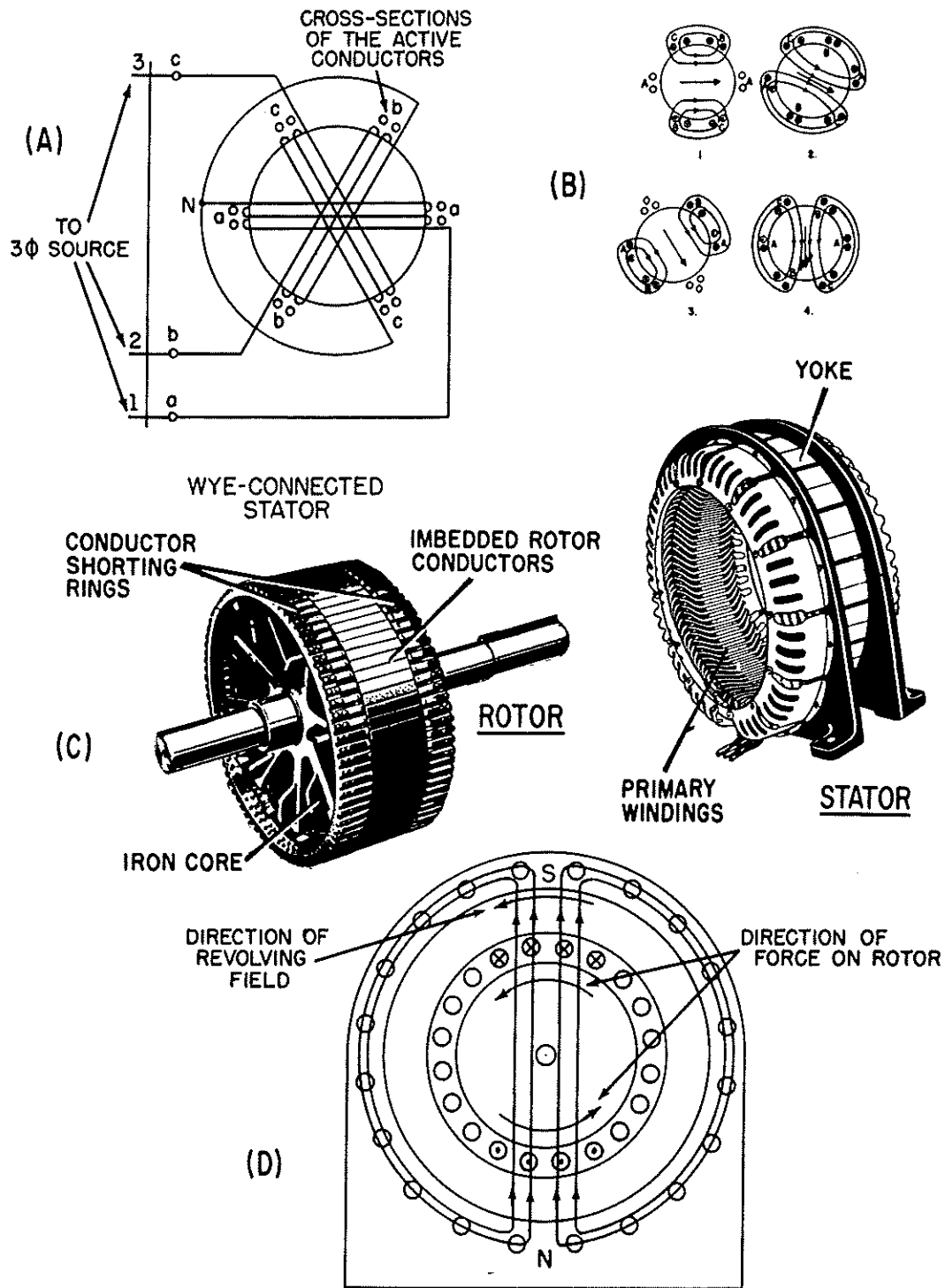


Figure 13-2.—Three-phase induction motor.

derives its name from the fact that mutual induction (transformer action) takes place between the stator and the rotor under operating conditions. The magnetic revolving field produced by the stator cuts across the rotor conductors, inducing a voltage in the conductors. This induced voltage causes rotor current to flow. Hence, motor torque is developed by the interaction of the rotor current and the magnetic revolving field.

Figure 13-2 (A) represents the winding of a 3-phase induction motor stator. Part (B) shows how the active stator conductors produce a rotating field, as previously described. Part (C) shows the essential parts of both stator and rotor. The purpose of the iron rotor core is to reduce air gap reluctance and to concentrate the magnetic flux through the rotor conductors. Induced current flows in one direction in half of the rotor conductors, and in the opposite direction in the remainder. The shorting rings on the ends of the rotor complete the path for rotor current. In part (D) a 2-pole field is assumed to be rotating in a counterclockwise direction at synchronous speed. At the instant pictured, the south pole field cuts across the upper rotor conductors from right to left, and the lines of force extend upward. Applying the left-hand rule for generator action to determine the direction of the voltage induced in the rotor conductors, the thumb is pointed in the direction of motion of the conductors with respect to the field. Since the field sweeps across the conductors from right to left, their relative motion with respect to the field is to the right. Hence the thumb points to the right. The index finger points upward and the second finger points into the page, indicating that the rotationally induced voltage in the upper rotor conductors is away from the observer.

Applying the left-hand rule to the lower rotor conductors and the north-pole field, the thumb points to the left, the index finger points upward, and the second finger points toward the observer, indicating that the direction of the rotationally induced voltage is out of the page. The rotor bars are connected to end rings that complete their circuits, and the rotationally induced voltages act in series addition to cause rotor currents to flow in the rotor conductors in the directions indicated. For simplification, the rotor currents are assumed to be in phase with the rotor voltages.

Motor action is analyzed by applying the right-hand rule for motors to the rotor conductors in figure 13-2 (D), to determine the direction of the force acting on the rotor conductors. For the upper rotor conductors, the index finger points upward, the second finger points into the page and the thumb points to the left, indicating that the force on the rotor tends to turn the rotor counterclockwise. This direction is the same as that of the rotating field. For the lower rotor conductors the index finger points upward, the second finger points toward the observer, and the thumb points toward the right, indicating that the force tends to turn the rotor counterclockwise—the same direction as that of the field.

The STATOR of a polyphase induction motor consists of a laminated steel ring with slots on the inside circumference. The motor stator winding is similar to the a-c generator stator winding and is generally of the two-layer distributed preformed type. Stator phase windings are symmetrically placed on the stator and may be either wye or delta connected.

There are two types of ROTORS—the CAGE ROTOR and the FORM-WOUND ROTOR. Both types have a laminated cylindrical core with parallel slots in the outside circumference to hold the windings in place. The cage rotor has an uninsulated bar winding; whereas the form-wound rotor has a two-layer distributed winding with preformed coils like those on a d-c motor armature.

CAGE ROTORS

A cage rotor is shown in figure 13-3 (A). The rotor bars are of copper, aluminum, or a suitable alloy placed in the slots of the rotor core. These bars are connected together at each end by rings of similar material. The conductor bars carry relatively large currents at low voltage. Hence, it is not necessary to insulate these bars from the core because the currents follow the path of least resistance and are confined to the cage winding.

FORM-WOUND ROTOR

A form-wound rotor (fig. 13-3 (B)) has a winding similar to 3-phase stator windings. Rotor windings are usually wye connected with the free ends of the winding connected to three slip rings mounted on the rotor shaft. An external variable wye-connected resistance (fig.

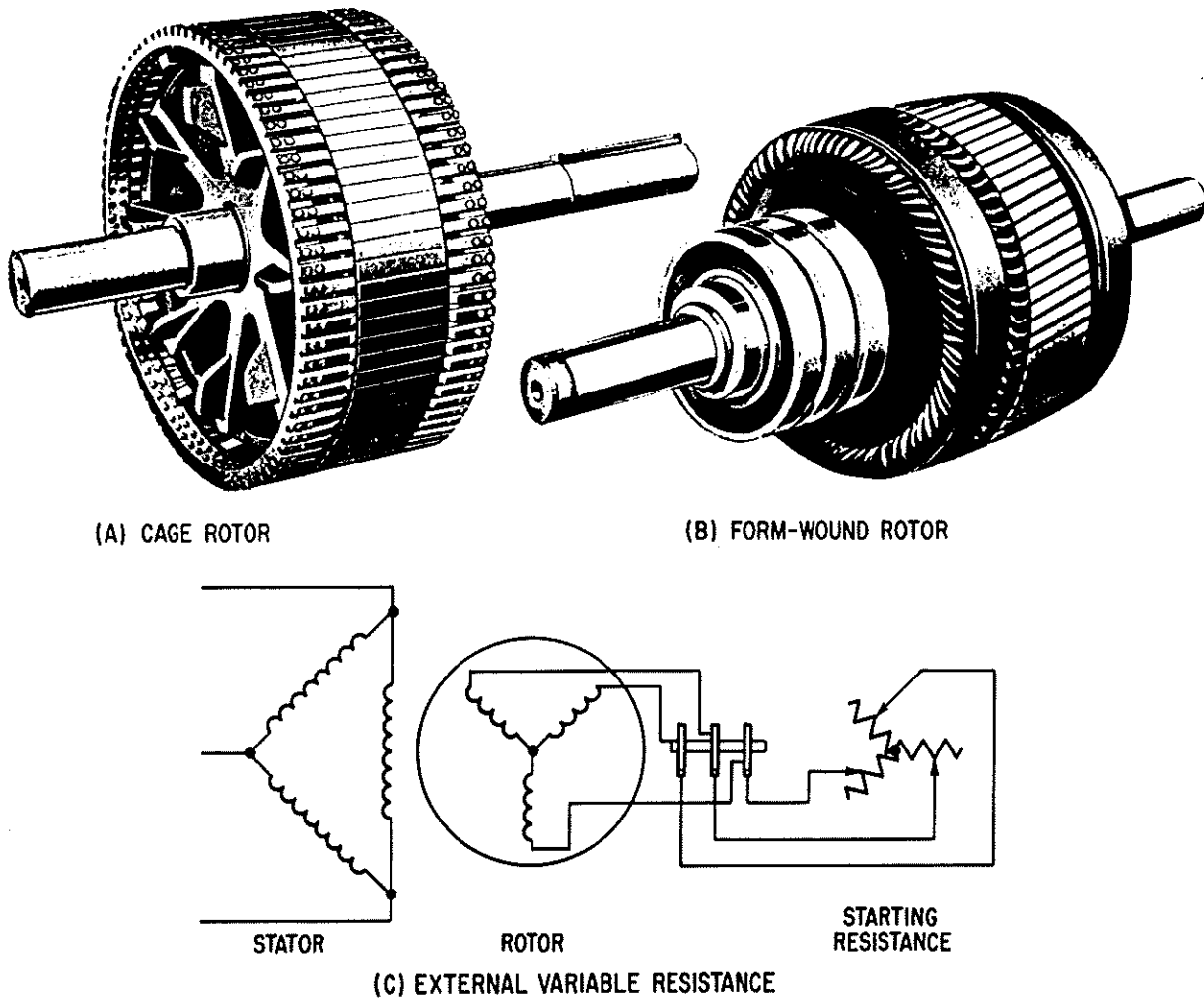


Figure 13-3.—Induction motor rotors.

13-3 (C)) is connected to the rotor circuit through the sliprings. The variable resistance provides a means of increasing the rotor-circuit resistance during the starting period to produce a high starting torque. As the motor accelerates, the rheostat is cut out. When the motor reaches full speed, the sliprings are short-circuited and the operation is similar to that of the cage motor.

TORQUE

As previously described, the revolving field produced by the stator windings cuts the rotor conductors and induces voltages in the conductors. Rotor currents flow because the rotor end-rings provide continuous metallic circuits.

The resulting torque tends to turn the rotor in the direction of the rotating field. This torque is proportional to the product of the rotor current, the field strength, and the rotor power factor.

The simplified cross section of a 2-pole cage-rotor motor is shown in figure 13-4. The magnetic field is rotating in a clockwise direction. Applying the left-hand rule for generator action, note that in figure 13-4 (A), the induced currents flow outward in the upper half and inward in the lower half of the rotor conductors. Applying the right-hand rule for motor action, note that the force acting on the rotor conductors is to the right on the upper group and to the left on the lower group.

As previously stated, a d-c motor receives its armature current by means of conduction through the commutator and brushes; whereas an induction motor receives its rotor current by means of induction. In this respect the induction motor is like a transformer with a rotating secondary. The primary is the stator which produces the revolving field; the secondary is the rotor. At start, the frequency of the rotor current is that of the primary stator winding. The reactance of the rotor is relatively large compared with its resistance, and the power factor is low and lagging by almost 90° . The rotor current therefore lags the rotor voltage by approximately 90° , as shown in figure 13-4(B). Because almost half of the conductors under the south pole carry current outward and the remainder of the conductors carry current inward, the net torque on the rotor as a result of the interaction between the rotor and the rotating field is small.

As the rotor comes up to speed in the same direction as the revolving field, the rate at which the revolving field cuts the rotor conductors is reduced and the rotor voltage and frequency of rotor currents are correspondingly reduced. Hence, at almost synchronous speed the voltage induced in the rotor is very small. The rotor reactance, X_L , also approaches zero, as may be seen from the relationship

$$X_L = 2\pi f_o L S,$$

where f_o is the frequency of the stator current, L the rotor inductance, and S the ratio of the difference in speed (between the stator field and the rotor) to the synchronous speed—that is, the slip. Slip is expressed mathematically as

$$S = \frac{N_s - N_r}{N_s},$$

where N_s is the number of revolutions per minute of the stator field, and N_r the number of revolutions per minute of the rotor. The frequency of the induced rotor current is $f_o S$.

In figure 13-4 (A), the rotor current is nearly in phase with the rotor voltage, and the direction of flow under the south pole is the same in all conductors. The torque would be ideally high except for the very small rotor current, which is produced by the low rotor voltage. The rotor voltage is proportional to the difference in speed between the rotor and the rotating field—that is, proportional to the slip.

The frequency of the rotor current varies directly with the slip. Thus, when the slip and the frequency of rotor current are almost zero,

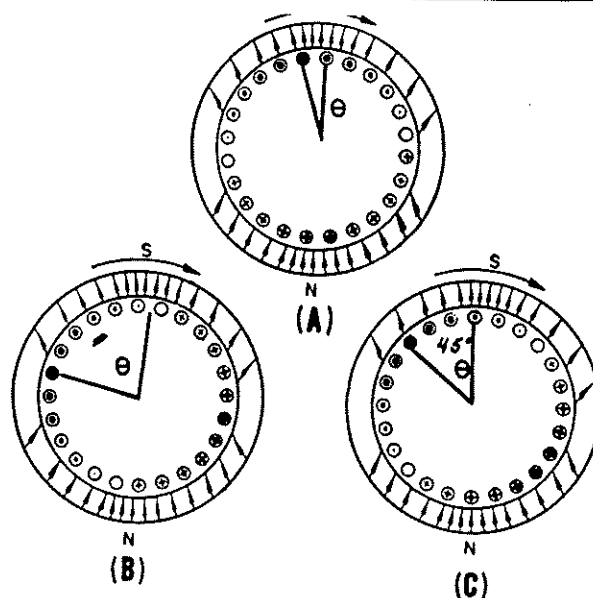


Figure 13-4.—Development of torque.

the rotor reactance and angle of lag are very small. When the rotor is starting, the difference in speed between the rotor and the rotating field is maximum; hence, the rotor reactance is maximum because the frequency of rotor current is maximum and approaches that of the line supplying the stator primary.

Normal operation is between these two extremes of rotor slip—that is, when the rotor is not turning at all or when it is turning almost at synchronous speed. The motor speed under normal load conditions is rarely more than 10 percent below synchronous speed. At the extreme of 100 percent slip, the rotor reactance is so high that the torque is low because of low power factor. At the other extreme of zero rotor slip, the torque is low because of low rotor current. The equation for torque, T , is

$$T = K \Phi I_r \cos \theta_r,$$

Where K is a constant, Φ the strength of the magnetic revolving field, I_r the rotor current, and $\cos \theta_r$ the power factor of the rotor current.

In the previous formula the product of rotor current and rotor power factor for a given strength of magnetic revolving field is a maximum value when the phase angle between rotor current and rotor induced voltage is 45° lagging, as indicated in figure 13-4, (C). In this case the reactance of the rotor equals the resistance of the rotor circuit, and the rotor power factor is 70.7 percent. This condition of operation is called

the PULL-OUT POINT. Beyond this point, the motor speed falls off rapidly with added load, and the motor stalls.

Variations in applied stator voltage affect the motor torque. This applied voltage establishes m.m.f.'s which create the rotating field. The rotating field, in turn, establishes the rotor current. Because rotor torque varies as the product of these factors, the torque of an induction motor varies as the square of the voltage applied to the stator primary winding.

The rotating field also sweeps across the stator winding which produces it. This action induces a counter e.m.f. in the winding. The counter e.m.f. opposes the applied voltage and limits the stator currents. If the applied voltage is increased to magnetic saturation, the counter e.m.f. is limited, and the primary current becomes dangerously high.

SYNCHRONOUS SPEED AND SLIP

The speed, N , of the rotating field is called the SYNCHRONOUS SPEED of the motor. As previously stated, the torque on the rotor tends to turn the rotor in the same direction as the revolving field. If the motor is not driving a load, it will accelerate to nearly the same speed as the revolving field. During the starting period, the increase in rotor speed is accompanied by a decrease in induced rotor voltage because the relative motion between the rotating field and rotor conductors is less. If it were possible for the rotor to attain synchronous speed there would be no relative motion between the rotor and the rotating field. There would then be no induced e.m.f. in the rotor, no rotor current, and thus no torque.

It is obvious that an induction motor cannot run at exactly synchronous speed. Instead, the rotor always runs just enough below synchronous speed at no load to establish sufficient rotor current to produce a torque equal to the resisting torque that is caused by the rotor losses.

The frequency of the alternating voltage induced in the rotor depends on the speed of the revolving field with respect to the rotor. One cycle of alternating voltage is induced in the rotor when the stator field sweeps completely around the rotor once. The rotor frequency, f_r , is directly proportional to the percent slip—

$$f_r = \frac{S f_s}{100}$$

where S is the percent slip and f_s is the frequency of the supply. For example, if the frequency of the supply is 60 cycles per second and the slip is 5 percent, the rotor frequency will be $\frac{5 \times 60}{100} = 3$ cycles per second. The frequency and magnitude of the induced rotor voltage decrease as the rotor speed increases. Both the rotor voltage and frequency would become zero if the rotor could attain synchronous speed.

LOSSES AND EFFICIENCY

The losses of an induction motor include (1) stator copper loss, $I_s^2 R_s$, and rotor copper loss, $I_r^2 R_r$; (2) stator and rotor core loss; and (3) friction and windage loss. For all practical purposes, the core, bearing friction, and windage losses are considered to be constant for all loads of an induction motor having a small slip. The power output may be measured on a mechanical brake or calculated from a knowledge of the input and the losses. The efficiency is equal to the ratio of the output power to input power; and at full load, it varies from about 85 percent for small motors to more than 90 percent for large motors.

CHARACTERISTICS OF THE CAGE-ROTOR MOTOR

As stated previously, the cage-rotor induction motor is comparable to a transformer with a rotating secondary. At no load, the magnetic revolving field produced by the primary stator winding cuts the turns of the stator winding. This action generates a counter e.m.f. in the stator winding, which limits the line current to a small value. This no-load value is called EXCITING CURRENT. Its function is to maintain the revolving field. Because the circuit is highly inductive, the power factor of the motor with no load is very poor. It may be as much as 30 percent lagging. Because there is no drag on the rotor, it runs at almost synchronous speed and the rotor current is quite small. Hence, the reaction of the rotor m.m.f. on the primary revolving field is small.

When load is added to the motor, the rotor slows down slightly; but the rotating field continues at synchronous speed. Therefore, the rotor current and slip increase. The motor torque increases more than the decrease in speed and the power output increases. The increased rotor m.m.f. opposes the primary field flux and lowers it slightly. The primary counter

e.m.f. therefore decreases slightly and primary current increases. The load component of primary current maintains the rotating field and prevents its further weakening because of the rotor-current opposition. Because of the relatively low internal impedance of the motor windings, a small reduction in speed and counter e.m.f. in the primary may be accompanied by large increases in motor current, torque, and power output. Thus, the cage-rotor motor has essentially constant-speed variable-torque characteristics.

If the induction motor is stalled by overload, the resulting increased rotor current lowers the primary counter e.m.f. and causes excessive primary current. This excessive current may damage the motor winding. When the rotor of an induction motor is locked, the voltage applied to the primary winding should not exceed 50 percent of its rated voltage.

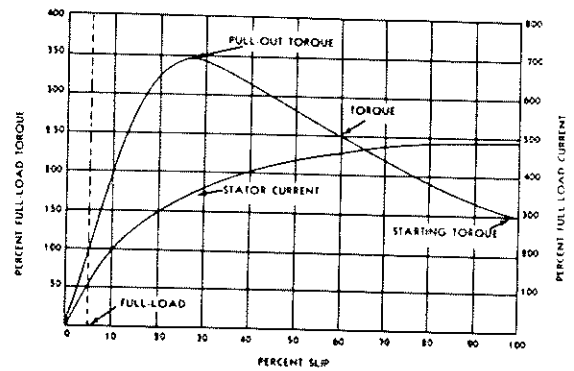
When the motor is operating at full load, the load component of stator current is more nearly in phase with the voltage across each stator phase because of the mechanical output (true power component) of the motor. The power factor is considerably improved over the no-load condition.

The torque and current curves for a 3-phase induction motor with cage rotor are shown in figure 13-5 (A). Rotor reactance increases with slip and increasingly affects the rotor current and power factor as the motor load is increased. The pull-out point on the torque curve occurs at about 25 percent slip. Maximum torque at this condition is about 3.5 times the normal full-load value, and, as previously mentioned, corresponds to a rotor power factor of 70.7 percent. Thus, for the pull-out condition, the rotor resistance equals the rotor reactance and the rotor power factor angle equals 45° . Any additional load on the motor beyond this point causes the rotor to pull out of its normal speed range and to stall quickly. At standstill, stator current is nearly 5 times normal; hence, constant-potential motor circuits like the one supplying this motor are equipped with time-delay automatic-overload protective devices. Sustained overload causes a circuit breaker to open and to protect both the motor and the circuit from damage.

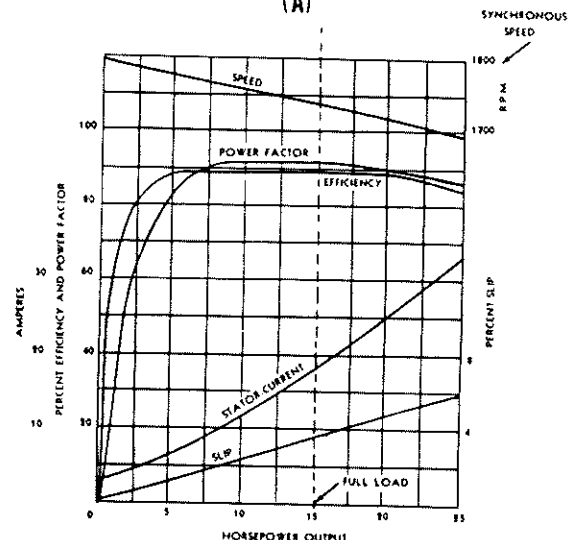
The performance curves of a 4-pole 3-phase 450-volt 15-horsepower cage-rotor motor are shown in figure 13-5 (B). The full-load slip is only about 3.5 percent. At standstill, the rotor reactance of this type of motor is nearly 5 times as great as the rotor resistance. At full load,

however, the rotor reactance is much less than the rotor resistance. When the motor is running, the rotor current is determined principally by the rotor resistance. The torque increases up to the pull-out point as the slip increases. Beyond this point the torque decreases and the motor stalls. Because the change in speed from no load to full load is relatively small, the motor torque and the horsepower output are considered to be directly proportional.

The cage-rotor induction motor has a fixed rotor circuit. The resistance and inductance of the windings are determined when the motor is designed and cannot be changed after it is built. The standard cage-rotor motor is a general-purpose motor. It is used to drive loads that



TORQUE AND CURRENT CURVES
(A)



PERFORMANCE CURVES FOR 4-POLE 3-PHASE
440-VOLT 15-HP CAGE-ROTOR MOTOR
(B)

Figure 13-5.—Characteristic curves of a cage-rotor motor.

require a variable torque at approximately constant speed with high full-load efficiency—such as blowers, centrifugal pumps, motor-generator sets, and various machine tools.

If the load requires special operating characteristics, such as high-starting torque, the cage rotor is designed to have high resistance. The starting current of a motor with a high-resistance rotor is less than that of a motor with a low-resistance rotor. The high-resistance rotor motor, like the cumulative compounded d-c motor, has wider speed variations than the low-resistance rotor motor. The high rotor resistance also increases the rotor copper losses, resulting in a lower efficiency than that of the low resistance type. These motors are used to drive cranes and elevators when high-starting torque and moderate-starting current are required and when it is desired to slow down the motor without drawing excessive currents.

CHARACTERISTICS OF WOUND-ROTOR MOTOR

The wound-rotor, or slipring, induction motor is used when it is necessary to vary the

rotor resistance in order to limit the starting current or to vary the motor speed. As previously explained, the starting torque may be made equal to the pull-out torque by increasing the rotor resistance to the point where it equals the rotor reactance at standstill. Maximum torque at start can be obtained with a wound-rotor motor with about 1.15 times full-load current; whereas a cage-rotor motor may require 5 times full-load current to produce maximum torque at start. Because the rotor-circuit copper losses are largely external to the rotor winding, the wound-rotor motor is desirable for an application which requires frequent starts.

The advantages of the wound-rotor induction motor over the cage-rotor induction motor are: (1) high-starting torque with moderate starting current, (2) smooth acceleration under heavy loads, (3) no excessive heating during starting, (4) good running characteristics, and (5) adjustable speed. The chief disadvantage of the wound-rotor is that the initial and maintenance costs are greater than those of the cage-rotor motor.

Synchronous Motors

The synchronous motor differs from the induction motor in several ways. The synchronous motor requires a separate source of d-c for the field. It also requires special starting components. These include a salient-pole field with starting grid winding. The rotor of the conventional type synchronous motor is essentially the same as that of the salient-pole a-c generator. The stator windings of induction and synchronous motors are essentially the same. The stator of a synchronous motor is illustrated in figure 13-6 (A).

If supplied with proper voltage, a d-c generator operates satisfactorily as a d-c motor, and there is practically no difference in construction and rating between the two. Similarly, an a-c generator becomes a synchronous motor if electric power is supplied to its terminals from an external source. Synchronous-motor rotating fields are generally of the salient-pole type, as shown in figure 13-6 (B).

Assume, for example, that two a-c generators of the salient-pole type are operating in parallel and feeding the same bus. If the prime mover is disconnected from one of the generators, it will become a synchronous motor and

continue to run at the same speed, drawing its power from the other a-c generator.

With the exception of certain modifications to make its operation more efficient and also to make it self-starting, the synchronous motor is very similar to the salient-pole rotating-field a-c generator. The rotor fields of both are separately excited from a d-c source, and both run at synchronous speeds under varying load conditions. An 8-pole generator rotor revolving at 900 r.p.m. generates 60 cycles per second; likewise, an 8-pole synchronous motor supplied with 60-cycle current will rotate at 900 r.p.m.

PRINCIPLE OF OPERATION

A polyphase current is supplied to the stator winding of a synchronous motor and produces a rotating magnetic field the same as in an induction motor. A direct current is supplied to the rotor winding, thus producing a fixed polarity at each pole. If it could be assumed that the rotor had no inertia and that no load of any kind were applied, then the rotor would revolve in step with the revolving field as soon as power was applied to both of the windings. This, however,

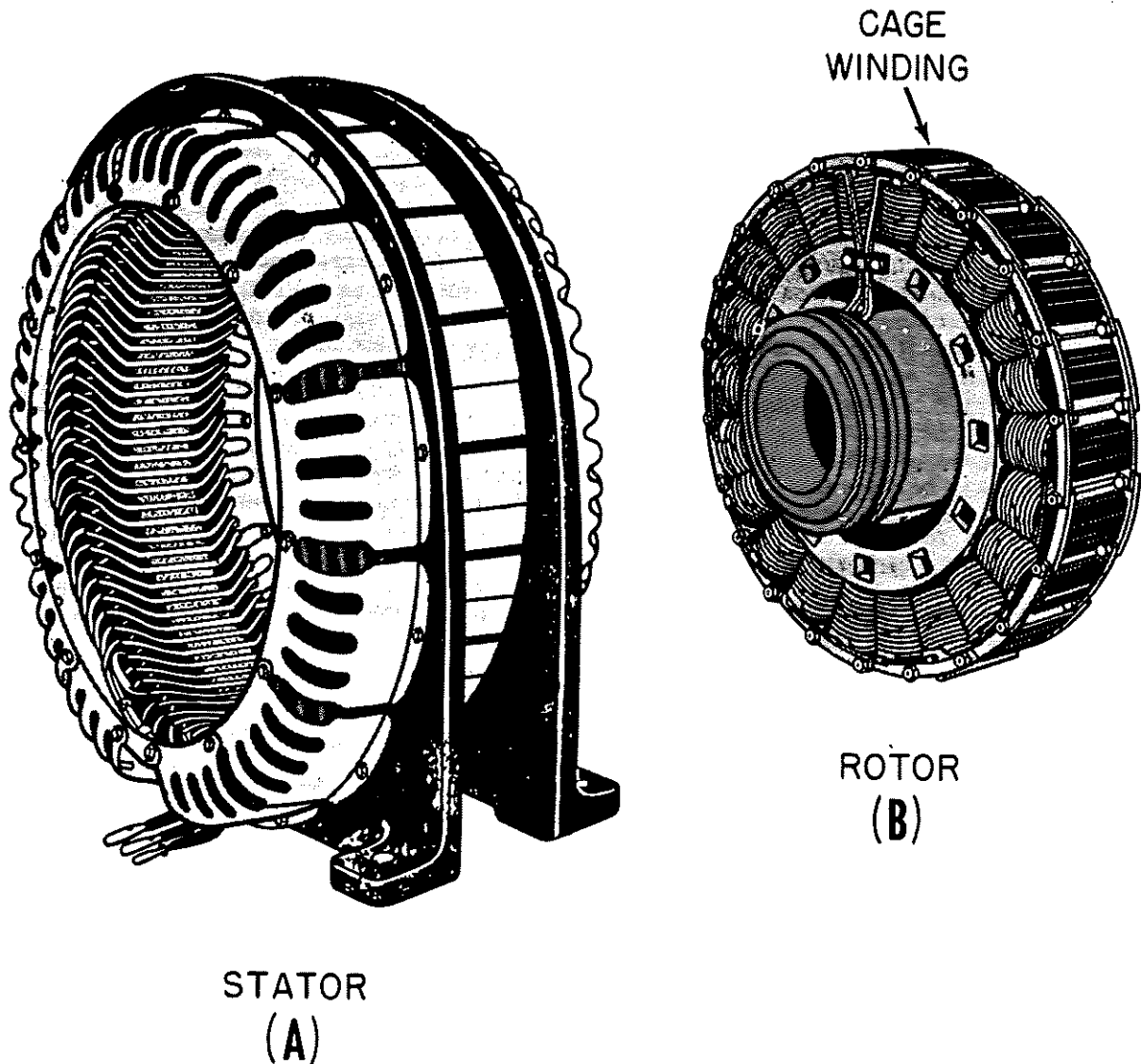


Figure 13-6.—Synchronous motor.

is not the case. The rotor has inertia, and in addition there is a load.

The reason a synchronous motor has to be brought up to synchronous speed by special means, may be understood from a consideration of figure 13-7.

If the stator and rotor windings are energized, then as the poles of the rotating magnetic field approach rotor poles of opposite polarity (fig. 13-7 (A)), the attracting force tends to turn the rotor in the direction opposite to that of the rotating field. As the rotor starts in this direction, the rotating-field poles are leaving the

rotor poles (fig. 13-7 (B)), and this tends to pull the rotor poles in the same direction as the rotating field. Thus, the rotating field tends to pull the rotor poles first in one direction and then in the other, with the result that the starting torque is zero.

STARTING

As has been explained, some type of starter must be used with the synchronous motor to bring the rotor up to synchronous speed. Although a small induction motor may be used to bring the rotor up to speed, this is not generally done.

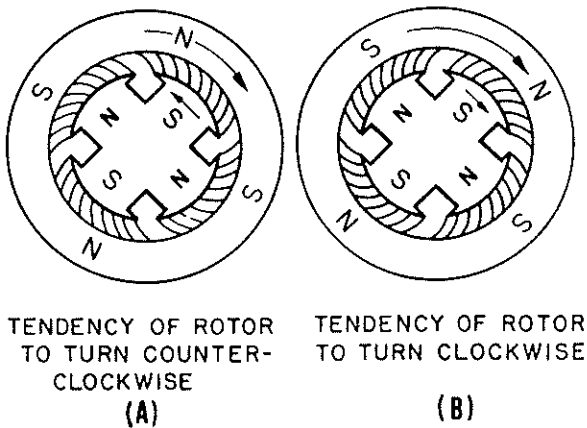


Figure 13-7.—Operating principle of synchronous motor.

Sometimes, if direct current is available, a d-c motor coupled to the rotor shaft may be used to bring the rotor up to synchronous speed. After synchronous speed is attained, the d-c motor is converted to operate as a generator to supply the necessary direct current to the rotor of the synchronous motor.

In general, however, another method is used to start the synchronous motor. A cage-rotor winding is placed on the rotor of the synchronous motor to make the machine self-starting as an induction motor. At start, the d-c rotor field is deenergized and a reduced polyphase voltage is applied to the stator windings. Thus, the motor starts as an induction motor and comes up to a speed which is slightly less than synchronous speed. The rotor is then excited from the d-c supply (generally a d-c generator mounted on the shaft), and the field rheostat adjusted for minimum line current.

If the armature has the correct polarity at the instant synchronization is reached, the stator current will decrease when the excitation voltage is applied. If the armature has the incorrect polarity, the stator current will increase when the excitation voltage is applied. This is a transient condition, and if the excitation voltage is increased further the motor will slip a pole and then come into step with the revolving field of the stator.

If the rotor d-c field winding of the synchronous machine is open when the stator is energized, a high a-c voltage will be induced in it because the rotating field sweeps through the large number of turns at synchronous speed.

It is therefore necessary to connect a resistor of low resistance across the rotor d-c field winding during the starting period. During the starting period, the d-c field winding is disconnected from the source and the resistor is connected across the field terminals. This permits alternating current to flow in the d-c field winding. Because the impedance of this winding is high compared with the inserted external resistance, the internal voltage drop limits the terminal voltage to a safe value.

STARTING TORQUE

Both the alternating currents induced in the rotor field winding and the cage-rotor winding during starting are effective in producing the starting torque. The torques produced by the rotor d-c field winding and the cage-rotor winding at different speeds are shown by the curves T_r and T_s , respectively, of figure 14-8. Curve T is the sum of T_r and T_s and indicates the total torque at different speeds during the starting period. Note that T_r is very effective in producing torque as the rotor approaches synchronous speed, but that both windings contribute no torque at synchronous speed because the induced voltage is zero and no d-c excitation is yet applied to the d-c winding.

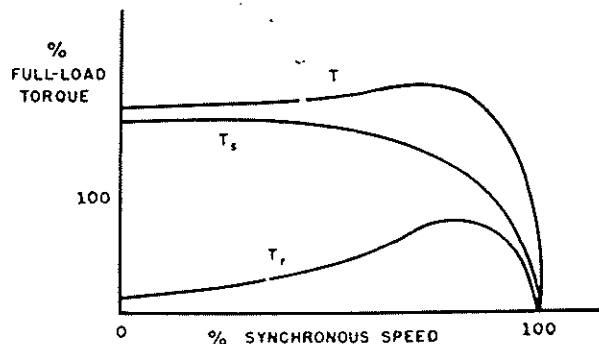


Figure 13-8.—Starting torque of a synchronous motor.

EFFECT OF VARYING LOAD AND FIELD STRENGTH

The power factor of an induction motor depends on the load and varies with it. The power factor of a synchronous motor carrying a definite load may be unity or less than unity, either lagging or leading, depending on the d-c field strength.

Alternating-Current Motor Starters

As in the case of d-c motors, some type of starter (controller) may also be employed on a-c motors to limit the initial inrush of current.

ACROSS-THE-LINE starters are the most common form aboard ship because of their simplicity and because ships are generally equipped with sufficient generating capacity to handle the high starting currents of the motors. This type of starter throws the stator winding of the motor directly across the main supply line. This may be feasible if the motor is not too large (5 horsepower or less) and if the generating capacity of the a-c generator can take care of the added load.

PRIMARY RESISTOR starters insert a resistor in the PRIMARY circuit (the stator circuit) of the motor for starting, or for starting and speed control. This starter is used when it is necessary to limit the starting current of a large a-c motor so as not to put too great a load on the system. If the resistor is used only during starting, its rating is based on intermittent operation, in which case it is relatively small and operates at a higher temperature. If the resistor is used also for speed control of small motors, such as for ventilating fans, its rating is based on continuous operation. In this case the resistor is relatively large and operates at a lower temperature.

SECONDARY RESISTOR starters insert a resistor in the secondary circuit (the rotor circuit of the form-wound type of induction motor) for starting and speed control. This starter may be used to limit starting currents, but is usually found where speed control of a large a-c motor is required, in which case the resistors are rated for continuous duty. Examples are some elevators and hoists equipped with direct a-c electric drives.

COMPENSATOR, or AUTOTRANSFORMER, starters start the motor at reduced voltage through an autotransformer, and subsequently connect the motor to full voltage after acceleration. The compensator may be either of two types.

1. The OPEN-TRANSITION type, during the transition period of shifting the motor from the autotransformer to direct connection with the supply lines, disconnects the motor from all power for a short period of time during which,

if the motor is of the synchronous type, it may coast and slip out of phase with the power supply. When the motor is then connected directly to the power lines, a high transition current may result.

2. The CLOSED-TRANSITION type keeps the motor connected to the power supply at all times during the transition period, thus not permitting the motor to decelerate. Accordingly, no high transition current is developed.

The AUTOTRANSFORMER starter is the most common form of the reduced-voltage type used for limiting the starting current of a motor. The open-transition form has the disadvantage of allowing a high transition current to develop, which can cause circuit breakers to open. The closed-transition form is preferable because no high transition current is developed.

REACTOR STARTERS insert a reactor in the primary circuit of an a-c motor during starting, and subsequently short-circuit the reactor to apply full voltage to the motor. This type of starter is not very widely used at present, but is becoming more common for starting large motors because it does not have the high transition current problem of the open-transition compensator and is smaller than the closed-transition compensator.

Assume that the line voltage is 100 volts and that when the taps on the autotransformer are positioned as shown in the starting position 40 volts will be applied to the 3-phase motor stator. With the reduction in motor voltage, there is a corresponding reduction in starting current drawn from the line. At the same time, the motor current supplied by the secondary low-voltage windings is proportionately increased by the transformer action.

After the proper time interval, during which acceleration occurs, full-line voltage is applied to the motor.

A resistance starter could be used in place of autotransformer to lower the voltage applied to the stator. The power factor would be improved, but the line current would be greater. The autotransformer has the advantage in permitting the motor to draw a relatively large starting current from the secondary with a relatively low line current.

Single-Phase Motors

Single-phase motors, as their name implies, operate on a single-phase power supply. These motors are used extensively in fractional horsepower sizes in the Navy and in commercial and domestic applications. The advantages of using single-phase motors in small sizes are that they are less expensive to manufacture than other types, and they eliminate the need for 3-phase a-c lines. Single-phase motors are used in interior communications equipment, fans, refrigerators, portable drills, grinders, and so forth.

A single-phase induction motor with only one stator winding and a cage rotor is like a 3-phase induction motor with a cage rotor except that the single-phase motor has no magnetic revolving field at start and hence no starting torque. However, if the rotor is brought up to speed by external means, the induced currents in the rotor will cooperate with the stator currents to produce a revolving field, which causes the rotor to continue to run in the direction in which it was started.

Several methods are used to provide the single-phase induction motor with starting torque. These methods identify the motor as split phase, capacitor, shaded pole, repulsion, and so forth.

Another class of single-phase motors is the a-c series (universal) type. Only the more commonly used types of single-phase motors are described. These include the (1) split-phase motor, (2) capacitor motor, (3) shaded-pole motor, (4) repulsion-start motor, and (5) a-c series motor.

SPLIT-PHASE MOTOR

The split-phase motor (fig. 13-12 (A)), has a stator composed of slotted laminations that contain an auxiliary (starting) winding and a running (main) winding. The axes of these two windings are displaced by an angle of 90 electrical degrees. The starting winding has fewer turns and smaller wire than the running winding, hence has higher resistance and less reactance. The main winding occupies the lower half of the slots and the starting winding occupies the upper half. The two windings are connected in parallel across the single-phase line supplying the motor. The motor derives its name from the action of the stator during the starting period. The single-phase stator is split into two windings (phases),

which are displaced in space by 90°, and which contain currents displaced in time phase by an angle of approximately 15° (fig. 13-12 (B)). The current, I_s , in the starting winding lags the line voltage by about 30° and is less than the current in the main winding because of the higher impedance of the starting winding. The current, I_m , in the main winding lags the applied voltage by about 45°. The total current, I_{line} , during the starting period is the vector sum of I_s and I_m .

At start, these two windings produce a magnetic revolving field that rotates around the stator air gap at synchronous speed. As the rotating field moves around the air gap, it cuts across the rotor conductors and induces a voltage in them, which is maximum in the area of highest field intensity and therefore is in phase with the stator field. The rotor current lags the rotor voltage at start by an angle that approaches 90° because of the high rotor reactance. The interaction of the rotor currents and the stator field cause the rotor to accelerate in the direction in which the stator field is rotating. During acceleration, the rotor voltage, current, and reactance

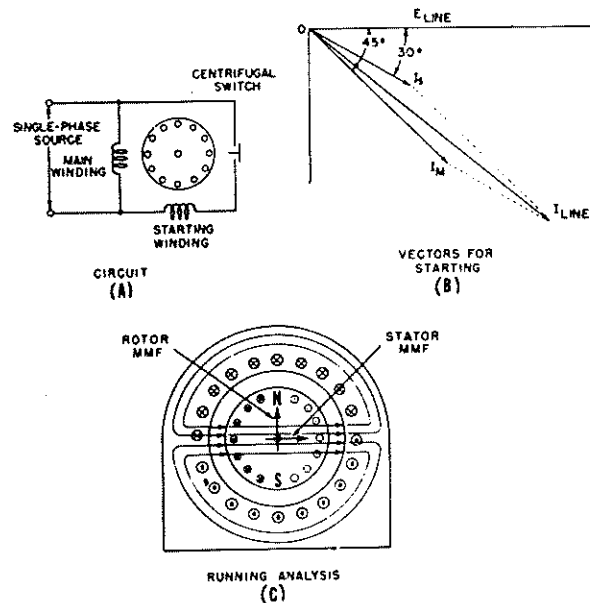


Figure 13-12.—Split-phase motor.

are reduced and the rotor currents come closer to an in-phase relation with the stator field.

When the rotor has come up to about 75 percent of synchronous speed, a centrifugally operated switch disconnects the starting winding from the line supply, and the motor continues

to run on the main winding alone. Thereafter, the rotating field is maintained by the interaction of the rotor magnetomotive force and the stator magnetomotive force. These two m.m.f.'s are pictured as the vertical and horizontal vectors respectively in the schematic diagram of figure 13-12 (C).

The stator field is assumed to be rotating at synchronous speed in a clockwise direction, and the stator currents correspond to the instant that the field is horizontal and extending from left to right across the air gap. The left-hand rule for magnetic polarity of the stator indicates that the stator currents will produce an *N* pole on the left side of the stator and an *S* pole on the right side. The motor indicated in the figure is wound for two poles.

Applying the left-hand rule for induced voltage in the rotor (the thumb points in the direction of motion of the conductor with respect to the field), the direction of induced voltage is back on the left side of the rotor and forward on the right side. The rotor voltage causes a rotor current to flow, which lags the rotor voltage by an angle whose tangent is the ratio of rotor

reactance to rotor resistance. This is a relatively small angle because the slip is small. Applying the left-hand rule for magnetic polarity to the rotor winding, the vertical vector pointing upward represents the direction and magnitude of the rotor m.m.f. This direction indicates the tendency to establish an *N* pole on the upper side of the rotor and an *S* pole on the lower side, as indicated in the figure. Thus, the rotor and stator m.m.f.'s are displaced in space by 90° and in time by an angle that is considerably less than 90° , but sufficient to maintain the magnetic revolving field and the rotor speed.

This motor has the constant-speed variable-torque characteristics of the shunt motor. Many of these motors are designed to operate on either 110 volts or 220 volts. For the lower voltage the stator coils are divided into two equal groups and these are connected in parallel. For the higher voltage the groups are connected in series. The starting torque is 150 to 200 percent of the full-load torque and the starting current is 6 to 8 times the full-load current. Fractional-horsepower split-phase motors are used in a variety of equipments such as washers, oil

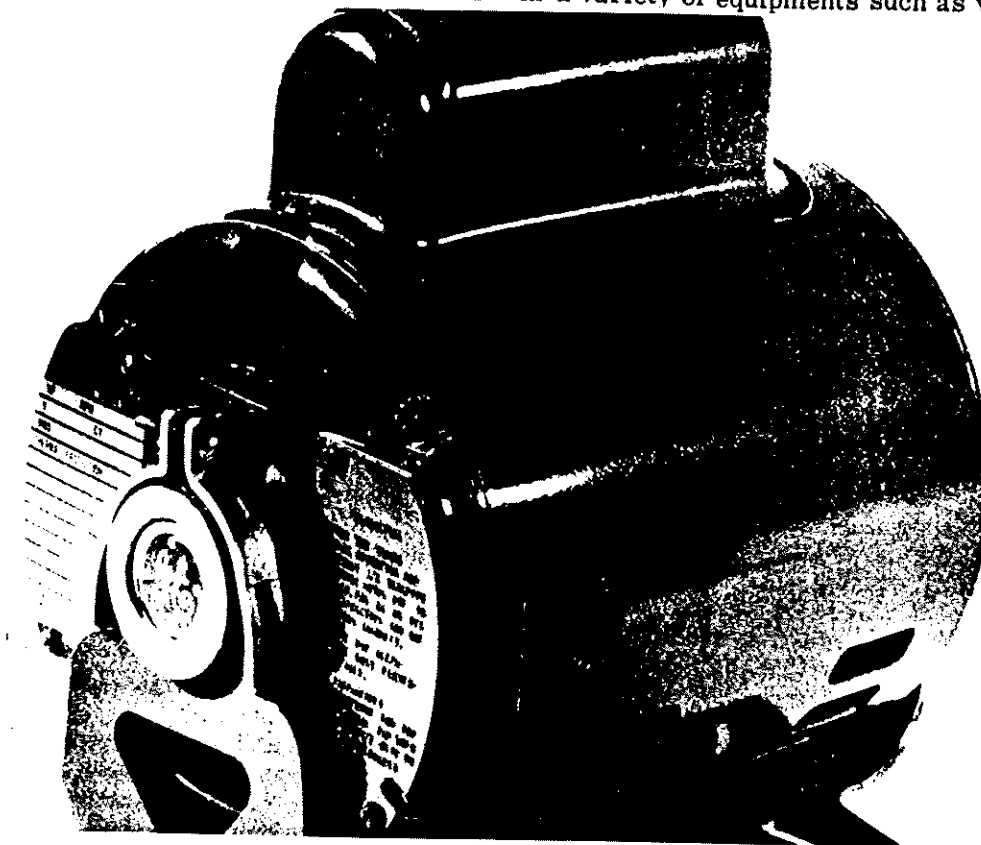


Figure 13-13 -Capacitor motor.

burners, and ventilating fans. The direction of rotation of the split-phase motor can be reversed by interchanging the starting winding leads.

CAPACITOR MOTOR

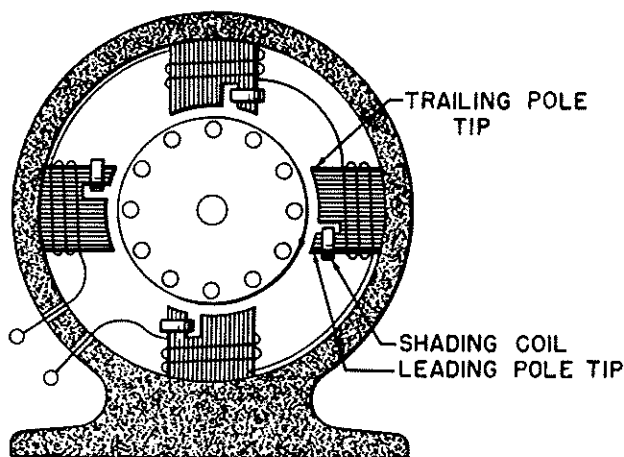
The capacitor motor is a modified form of split-phase motor, having a capacitor in series with the starting winding. An external view is shown in figure 13-13, with the capacitor located on top of the motor. The capacitor produces a greater phase displacement of currents in the starting and running windings than is produced in the split-phase motor. The starting winding is made of many more turns of larger wire and is connected in series with the capacitor. The starting winding current is displaced approximately 90° from the running winding current. Since the axes of the two windings are also displaced by an angle of 90° , these conditions produce a higher starting torque than that of the split-phase motor. The starting torque of the capacitor motor may be as much as 350 percent of the full-load torque.

If the starting winding is cut out after the motor has increased in speed, the motor is called a **CAPACITOR-START MOTOR**. If the starting winding and capacitor are designed to be left in the circuit continuously, the motor is called a **CAPACITOR MOTOR**. Electrolytic capacitors for capacitor-start motors vary in size

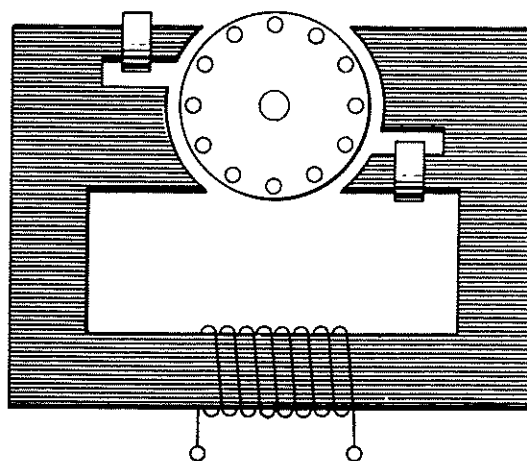
from about 80 microfarads for 1/8-horsepower motors to 400 microfarads for one-horsepower motors. Capacitor motors of both types are made in sizes ranging from small fractional horsepower motors up to about 10 horsepower. They are used to drive grinders, drill presses, refrigerator compressors, and other loads that require relatively high starting torque. The direction of rotation of the capacitor motor may be reversed by interchanging the starting winding leads.

SHADED-POLE MOTOR

The shaded-pole motor employs a salient-pole stator and a cage rotor. The projecting poles on the stator resemble those of d-c machines except that the entire magnetic circuit is laminated and a portion of each pole is split to accommodate a short-circuited copper strap called a **SHADING COIL** (fig. 13-14). This motor is generally manufactured in very small sizes, up to 1/20 horsepower. A 4-pole motor of this type is illustrated in figure 13-14 (A). The shading coils are placed around the leading pole tip and the main pole winding is concentrated and wound around the entire pole. The 4 coils comprising the main winding are connected in series across the motor terminals. An inexpensive type of 2-pole motor employing shading coils is illustrated in figure 13-14 (B).



(A)
FOUR-POLE MOTOR



(B)
TWO-POLE MOTOR

Figure 13-14.—Shaded-pole motor.

During that part of the cycle when the main pole flux is increasing, the shading coil is cut by the flux, and the resulting induced e.m.f. and current in the shading coil tend to prevent the flux from rising readily through it. Thus, the greater portion of the flux rises in that portion of the pole that is not in the vicinity of the shading coil. When the flux reaches its maximum value, the rate of change of flux is zero, and the voltage and current in the shading coil also are zero. At this time the flux is distributed more uniformly over the entire pole face. Then as the main flux decreases toward zero, the induced voltage and current in the shading coil reverse their polarity, and the resulting magnetomotive force tends to prevent the flux from collapsing through the iron in the region of the shading coil. The result is that the main flux first rises in the unshaded portion of the pole and later in the shaded portion. This action is equivalent to a sweeping movement of the field across the pole face in the direction of the shaded pole. The cage rotor conductors are cut by this moving field and the force exerted on them causes the rotor to turn in the direction of the sweeping field.

Most shaded-pole motors have only one edge of the pole split, and therefore the direction of rotation is not reversible. However, some shaded-pole motors used in fire control and interior communications circuits have both leading and trailing pole tips split to accommodate shading coils. The leading pole tip shading coils form one series group, and the trailing pole tip shading coils form another series group. Only the shading coils in one group are simultaneously active, while those in the other group are on open circuit.

The shaded-pole motor is similar in operating characteristics to the split-phase motor. It has the advantages of simple construction and low cost. It has no sliding electrical contacts and is reliable in operation. However, it has low starting torque, low efficiency, and high noise level. It is used to operate small fans. The shading coil and split pole are used in clock motors to make them self-starting.

REPULSION-START MOTOR

The repulsion-start motor has a form-wound rotor with commutator and brushes. The stator is laminated and contains a distributed single-

phase winding. In its simplest form, the stator resembles that of the single-phase motor. In addition, the motor has a centrifugal device which removes the brushes from the commutator and places a short-circuiting ring around the commutator. This action occurs at about 75 percent of synchronous speed. Thereafter, the motor operates with the characteristics of the single-phase induction motor.

The starting torque of the repulsion-start induction motor is developed through the interaction of the rotor currents and the single-phase stator field. Unlike the split-phase motor, the stator field does not rotate at start, but alternates instead. The rotor currents are induced through transformer action. For example, in the 2-pole motor of figure 13-15 (A), the stator currents are shown for the instant when a north pole is established on the upper side of the stator, and a south pole on the lower side. The induced voltage in the rotor causes the rotor currents to flow in such a direction as to oppose the stator field. These currents flow in opposite directions under the left and right portions of the north pole and in similar manner under the south pole. Thus, the net force to turn the rotor is zero when the brushes are located in the positions shown.

In figure 13-15 (B), the brushes are moved 90° from their original positions, and again there is no rotor turning effort because in this case the rotor current is zero. There can be no rotor current in this position because the transformer induced voltages are equal and opposite to each other in the two halves (upper and lower) of the rotor winding.

In figure 13-15 (C), the brush axis is displaced from the stator polar axis by an angle of about 25°, and in this position maximum torque is developed.

The direction of the induced currents in the rotor under the north pole of the stator is toward the observer, and under the south pole, away from the observer. Applying the right-hand rule for motors, the force acting on the conductors under the north pole is toward the left, and under the south pole, toward the right, thus tending to turn the rotor in a counterclockwise direction. When the stator polarity reverses, the direction of the rotor current also reverses, thereby maintaining the same direction of rotation. The function of the commutator and brushes is to divide the rotor currents along an axis that is

displaced from the axis of the stator field in a counterclockwise direction. The motor derives its name from the repulsion of like poles between the rotor and stator. Thus, the rotor currents establish the rotor poles $N'-S'$, which are repelled by the stator poles $N-S$.

The starting torque is 250 to 450 percent of the full-load torque, and the starting current is 375 percent of the full-load current. This motor is made in fractional horsepower sizes and in larger sizes up to 15 horsepower, but has been replaced in large parts by the cheaper and more rugged capacitor motor. The repulsion-start motor has higher pull-out torque (torque at which the motor stalls) than the capacitor-start motor, but the capacitor start motor can bring up to full speed loads that the repulsion motor can start but cannot accelerate.

A-C SERIES MOTOR

The a-c series motor will operate on either a-c or d-c circuits. It will be recalled that the direction of rotation of a d-c series motor is independent of the polarity of the applied voltage, provided the field and armature connections remain unchanged. Hence, if a d-c series motor is connected to an a-c source, a torque will be developed which tends to rotate the armature in one direction. However, a d-c series motor does not operate satisfactorily from an a-c supply for the following reasons:

1. The alternating flux sets up large eddy-current and hysteresis losses in the unlaminated portions of the magnetic circuit and causes excessive heating and reduced efficiency.
2. The self-induction of the field and armature windings causes a low power factor.
3. The alternating field flux establishes large currents in the coils that are short-circuited by the brushes; this action causes excessive sparking at the commutator.

To design a series motor for satisfactory operation on alternating current the following changes are made:

1. The eddy-current losses are reduced by laminating the field poles, yoke, and armature.
2. Hysteresis losses are minimized by using high-permeability transformer-type silicon-steel laminations.
3. The reactance of the field windings is kept satisfactorily low by using shallow pole pieces, few turns of wire, low frequency (usually 25 cycles for large motors), low flux density, and low reluctance (a short air gap).

4. The reactance of the armature is reduced by using a compensating winding embedded in the pole pieces. If the compensating winding is connected in series with the armature (fig. 14-16 (A)), the armature is **CONDUCTIVELY** compensated. If the compensating winding is short-circuited on itself (fig. 13-16 (B)), the armature is **INDUCTIVELY** compensated. If the motor is designed for operation on both d-c and a-c circuits, the compensating winding is connected in series with the armature. The axis of the compensating

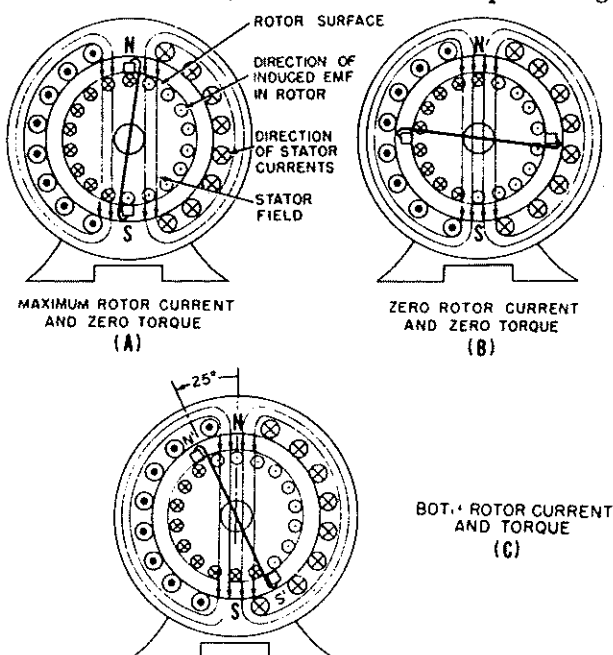


Figure 13-15.—Repulsion-start induction motor.

winding is displaced from the main field axis by an angle of 90° . This arrangement is similar to the compensating winding used in some d-c motors and generators to overcome armature reaction. The compensating winding establishes a counter magnetomotive force which neutralizes the effect of the armature magnetomotive force, thereby preventing distortion of the main field flux and reducing the armature reactance. The inductively compensated armature acts like the primary of a transformer, the secondary of which is the shorted compensating winding. The shorted secondary receives an induced voltage by the action of the alternating armature flux, and the resulting current flowing through the turns of the compensating winding establish the opposing magnetomotive force that neutralizes the armature reactance.

5. Sparking at the commutator is reduced by the use of PREVENTIVE LEADS P_1, P_2, P_3 , and so forth (fig. 13-16 (C)). A ring armature is shown for simplicity. When coils at A and B are shorted by the brushes, the induced current is limited by the relatively high resistance of the leads. Preventive leads are used in some of the older type a-c series motors on electric locomotives. Sparking at the brushes is also reduced by using armature coils having only a single turn and multipolar fields. High torque is obtained by having a large number of armature conductors and a large-diameter armature. Thus, the commutator has a large number of commutator bars that are very thin, so that the armature voltage is limited to about 250 volts.

The operating characteristics of the a-c series motor are similar to those of the d-c series motor. The speed will increase to a dangerously high value if the load is removed from the motor.

Fractional horsepower a-c series motors are called UNIVERSAL MOTORS. They do not have compensating windings or preventive leads. They are used extensively in the Navy to operate fans and portable tools, such as drills, grinders, and saws.

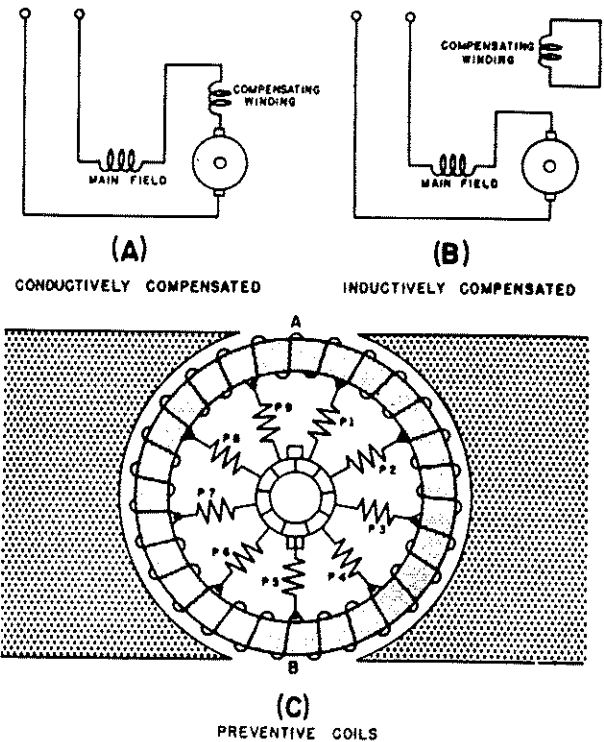


Figure 13-16. A-c series motor.

QUIZ

- The variable resistance placed in the rotor circuit of the form-wound rotor is for the purpose of
 - speed control
 - frequency control
 - voltage control
 - starting torque control
- The most common method of starting a synchronous motor is
 - with a separate d-c motor
 - with a cage-rotor winding
 - manually
 - by applying d. c. to the rotor
- Why does the capacitor motor have a higher starting torque than a split-phase motor? It has
 - a higher power factor
 - no displacement between start and main winding currents
 - less displacement between start and main winding currents
 - greater displacement between its start and main winding currents
- The synchronous speed of an induction motor is the
 - speed at which the rotor turns
 - speed of the rotating field
 - frequency of the rotor current
 - slip in percent of rotor r.p.m.
- Near synchronous speed, the
 - voltage induced into the rotor is very small
 - voltage induced into the rotor is large
 - applied voltage on the stator is zero
 - rotor frequency is maximum
- What circumstances cause a lagging power factor?
 - I_s lags resultant E by 90° - I_s lags E_a by angle θ
 - I_s leads resultant E by 90° - I_s leads E_a by angle θ
 - resultant E lags I_s by 90° - I_s lags E_a by angle ϕ
 - E_c leads I_s by 90° - I_s leads E_a by angle ϕ

ALTERNATING-CURRENT MOTORS

7. What is the direction of rotation of the shaded-pole motor in respect to the sweeping field?
 - a. With the sweeping field
 - b. Against the sweeping field
 - c. Toward the unshaded tip
 - d. Depends on direction motor was started
8. Increasing the number of poles in an induction motor
 - a. increases the field speed
 - b. decreases the field speed
 - c. decreases the motor's rated torque
 - d. causes the frequency of line E to drop
9. The rotor voltage is proportional to the
 - a. strength of the magnetic field
 - b. number of conductors on the stator
 - c. angle at which lines of force are cut
 - d. difference in rotor speed and the speed of the rotating field
10. The most common type of starter used on board ship for a-c motors is the
 - a. autotransformer
 - b. secondary capacitor
 - c. primary resistor
 - d. across-the-line
11. In the repulsion induction motor, what is the position of the brushes in relation to the stator polar axis for maximum torque?
 - a. 15°
 - b. 25°
 - c. 45°
 - d. 90°
12. Increasing the frequency of the voltage applied to an induction motor causes the
 - a. field speed to decrease
 - b. field speed to increase
 - c. rotor torque to decrease
 - d. stator current to increase
13. The purpose of the iron rotor core is to
 - a. decrease motor weight
 - b. produce eddy currents
 - c. reduce air gap reluctance
 - d. decrease permeability
14. The frequency of rotor current varies directly with
 - a. applied voltage
 - b. the resistance of the rotor
 - c. the slip
 - d. the number of windings on the stator
15. The efficiency of a motor is equal to the
 - a. torque output at synchronous speed
 - b. amount of current in the rotor
 - c. horsepower of the motor
 - d. ratio of its output power to its input power
16. The type of starter used when it is necessary to limit the starting current of an a-c motor is the
 - a. autotransformer
 - b. secondary resistor
 - c. primary resistor
 - d. primary capacitor
17. The type of starter used for speed control of an a-c motor is the
 - a. secondary resistor
 - b. open transition
 - c. closed transition
 - d. primary resistor
18. Motor action is best analyzed by applying
 - a. Fleming's right-hand rule
 - b. the magnetic laws of polarity
 - c. Lenz's law for self-induced voltage
 - d. the left-hand motor rule
19. A synchronous motor is not self-starting due to
 - a. its lack of a rotating magnetic field
 - b. inertia of the rotor
 - c. magnetic locking action between rotor and stator fields
 - d. its low power factor
20. The single-phase a-c motor is not self-starting because there is
 - a. inertia in the rotor
 - b. no high starting torque
 - c. no revolving magnetic field
 - d. a magnetic lock between the rotor and stator
21. In the a-c series motor, how are hysteresis losses minimized? By use of
 - a. high frequency voltage
 - b. laminations only
 - c. hard iron
 - d. silicone steel
22. The direction of rotation of an induction motor is
 - a. opposite the rotating field direction
 - b. same as direction of rotating field
 - c. determined by the number of poles
 - d. determined by the location of its brushes
23. A synchronous motor differs from an induction motor in that it
 - a. is not self-starting
 - b. requires an a-c and a d-c power supply
 - c. may be used for power factor correction
 - d. all of the above
24. How can the direction of rotation of a split-phase induction motor be reversed?
 - a. Reverse leads of main winding
 - b. Reverse leads of start windings
 - c. Reverse leads of one phase
 - d. Reverse any two leads
25. Fractional horsepower a-c series motors are called
 - a. induction motors
 - b. synchronous motors
 - c. universal motors
 - d. shaded-pole motors

CHAPTER 14

DIRECT-CURRENT GENERATORS

Generators can be designed to supply small amounts of power or they can be designed to supply many thousands of kilowatts of power. Also, generators may be designed to supply either direct current or alternating current. Direct-current generators are described in this chapter. Alternating-current generators were described

A d-c generator is a rotating machine that converts mechanical energy into electrical energy. This conversion is accomplished by rotating an armature, which carries conductors, in a magnetic field, thus inducing an e.m.f. in the conductors. As stated before, in order for an e.m.f. to be induced in the conductors, a relative motion must always exist between the conductors and the magnetic field in such a manner that the conductors cut through the field. In most d-c generators the armature is the rotating member and the field is the stationary member. A mechanical force is applied to the shaft of the rotating member to cause the relative motion. Thus, when mechanical energy is put into the machine in the form of a mechanical force or twist on the shaft, causing the shaft to turn at a certain speed, electrical energy in the form of voltage and current is delivered to the external load circuit.

It should be understood that mechanical power must be applied to the shaft constantly so long as the generator is supplying electrical energy to the external load circuit.

The power source used to turn the armature is commonly called a PRIME MOVER. Many forms of prime movers are in use, such as steam turbines, diesel engines, gasoline engines, and steam engines. However, the principal sources of power aboard ship are steam turbines and diesel engines. Also, auxiliary power units containing d-c generators driven by gasoline engines are widely used in naval maintenance operations.

In aviation, aircraft engines function as prime movers for both a-c and d-c generating equipment.

A d-c generator consists essentially of (1) a steel frame or yoke containing the pole pieces and field windings, (2) an armature consisting of a group of copper conductors mounted in a slotted cylindrical core, made up of thin steel disks called LAMINATIONS, (3) a commutator for maintaining the current in one direction through the external circuit, and (4) brushes with brush holders to carry the current from the commutator to the external load circuit.

Though both contain the same essential parts, the shipboard d-c generator and the d-c generator used on aircraft are quite different in size, rating, and appearance. A typical generator used aboard ship is shown in figure 14-1 (A); an aircraft generator is shown in part (B). Shipboard generators may weigh thousands of pounds and be rated in the hundreds of kilowatts. Aircraft generators rarely exceed eighty pounds in weight or nine kilowatts in rating.

Construction

FRAME

The d-c generator field frame, or yoke, is usually made of annealed steel. The use of steel reduces the reluctance of the magnetic circuit to a low value and therefore reduces the necessary size of the field windings. The frame pro-

vides a mechanical support for the pole pieces and serves as a portion of the magnetic circuit to provide the necessary flux across the air gap.

The end bells are bolted to the frame structure and support the armature shaft bearings. One end bell also supports the brush rigging and extends over the commutator.

DIRECT-CURRENT GENERATORS

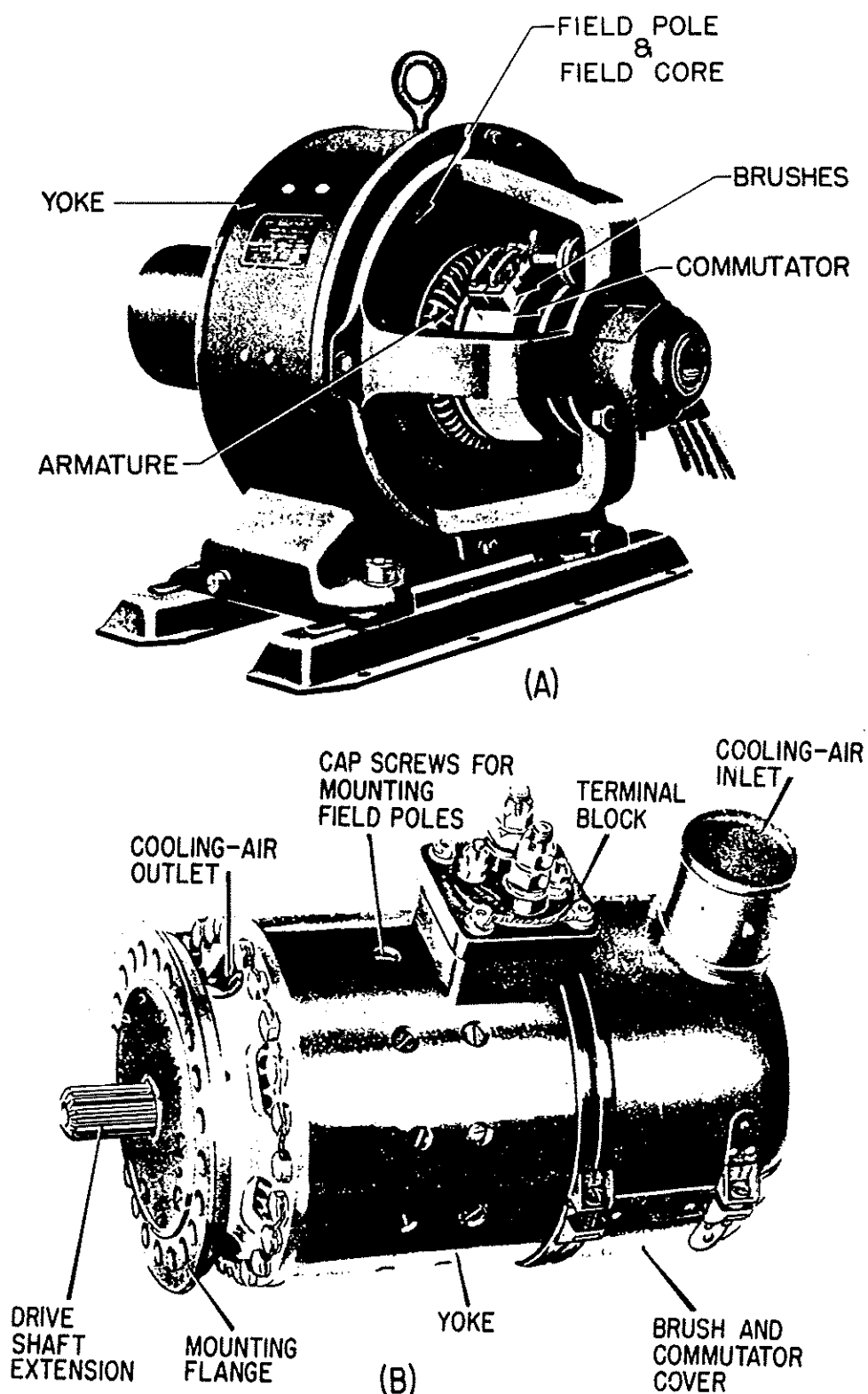


Figure 14-1.—D-c generators.

FIELD WINDINGS

The field windings are connected so that they produce alternate north and south poles (fig. 14-2 (A) and (F)) to obtain the correct direction of e.m.f. in the armature conductors. The field windings form an electromagnet which establishes the generator field flux. These field windings may receive current from an external d-c source or they may be connected directly across the armature, which then becomes the source of voltage. When they are so energized, they establish magnetic flux in the field yoke, pole pieces, air gap, and armature core, as shown in figure 14-2 (A).

POLE PIECES

The pole pieces, which support the field windings, are mounted on the inside circumference of the yoke, with capscrews that extend through the frame (fig. 14-1). These pole pieces are usually built of sheet steel laminations riveted together. The pole faces are shaped to fit the curvature of the armature, as shown in figure 14-2 (A). The preformed field coil shown in figure 14-2 (B) is mounted on the laminated core from the back. The coil is held securely in place between the frame and the flanged end of the pole.

ARMATURE

The armature (fig. 14-2 (C)) is mounted on a shaft and rotates through the field. If the output of the armature is connected across the field windings, the voltage and the field current at start will be small because of the small residual flux in the field poles. However, as the generator continues to run, the small voltage across the armature will circulate a small current through the field coils and the field will become stronger. This action causes the generator voltage to rise quickly to the proper value and the machine is said to "build up" its voltage.

The armature core is made of sheet steel laminations. In small machines these laminations are keyed directly to the shaft. In large machines the laminations are assembled on a spider which is keyed to the shaft. The outer surface of this cylindrical core is slotted to provide a means of securing the armature coils. Radial ventilating ducts are provided in the core by inserting spacers between the laminations at definite intervals. These ducts permit air to circulate through the core and to carry off heat

produced in the armature winding and core. The armature coils on most generators are form-wound to the correct size and shape. Additional insulation between the core and windings is obtained by placing sheet insulation in the slots. The windings are secured by fiber wedges driven into the tops of the slots. The free ends of the armature coils are connected to the commutator riser, as indicated in figure 14-2 (C). The entire armature winding forms a closed circuit.

COMMUTATOR

The commutator consists of a number of wedge-shaped segments, or bars, of hard drawn copper that are assembled into a cylinder and held together by V-rings, as shown in figure 14-2 (D). The commutator segments are insulated from each other by sheet mica and the entire commutator is insulated from the supporting rings on the shaft by mica collars. Because the brushes bear on the outside surface of the commutator, better brush contact, less sparking, and less noise, are obtained by undercutting the mica to about 1/64 inch below the level of the commutator surface. The voltage and the number of poles in the generator determine the number of commutator segments. To prevent flashover between segments, generators are designed so that a voltage not to exceed 15 volts exists between adjacent segments. Therefore, a high-voltage generator requires more commutator segments than a low-voltage generator.

BRUSHES AND BRUSH HOLDERS

The brushes carry the current from the commutator to the external circuit. They are usually made of a mixture of carbon and graphite. For low-voltage machines the brushes are made of a mixture of graphite and a metallic powder. The brushes must be free to slide in their holders (fig. 14-2 (E)) so that they may follow any small irregularities in the curvature of the commutator. In addition, the brushes must be able to "feed in" as they wear. However, excessive play not only would encourage brush vibration, but also might cause misalignment of the brush with the axis of commutation. This would result in excessive sparking.

The proper pressure of the brushes against the commutator is maintained by means of springs and should be from 1-1/2 to 2 pounds per square inch of brush contact area. A low resistance connection between the brushes and

DIRECT-CURRENT GENERATORS

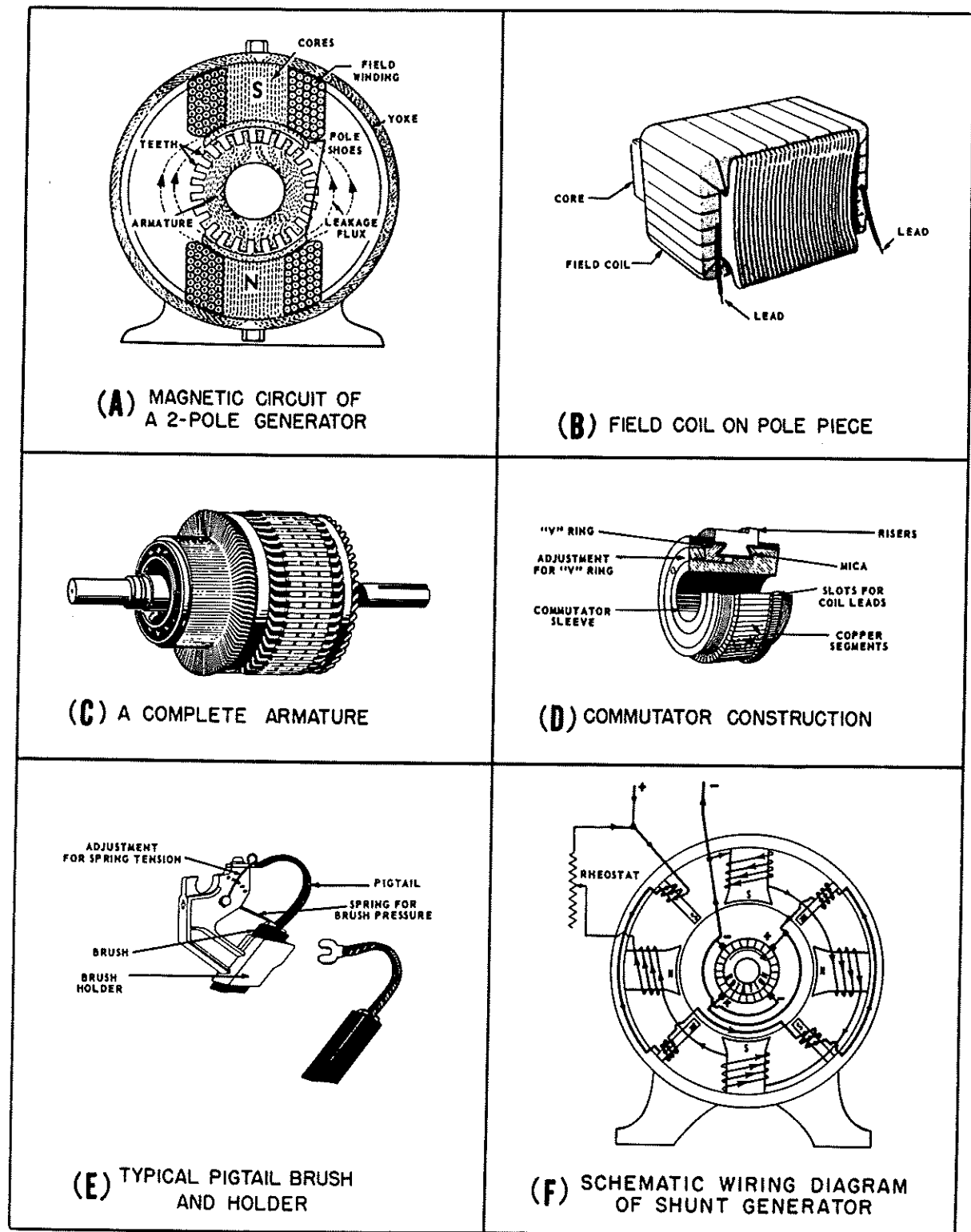


Figure 14-2.—D-c generator parts.

brush holders is maintained by means of braided copper wires, or pigtails, that are attached between each brush holder and brush.

The brush holders, which are attached to brush studs, hold the brushes in their proper positions on the commutator. The brush studs

are fastened to a rocker arm, or brush holder yoke, that is attached to the frame. Multipolar generators usually have as many brush studs as there are main poles. The brush studs are of alternate positive and negative polarity and those of like polarity are connected together as indicated in figure 14-2 (F).

Armature Windings

SIMPLE COIL ARMATURE

The simplest generator armature winding is a loop or single coil. Rotating this loop in a magnetic field will induce an e.m.f. whose strength is dependent upon the strength of the magnetic field and the speed of rotation of the conductor.

A single-coil generator with each coil terminal connected to a bar of a 2-segment metal ring is shown in figure 14-3. The two segments of the split ring are insulated from each other and the shaft, thus forming a simple commutator. The commutator mechanically reverses the armature coil connections to the external circuit at the same instant that the direction of the generated voltage reverses in the armature coil. This action involves the process known as commutation, which is described later in the chapter.

When the coil rotates clockwise from the position shown in figure 14-3 (A), to the position shown in figure 14-3 (B), an e.m.f. is generated in the coil in the direction (indicated by the heavy arrows) that deflects the galvanometer to the right. Current flows out of the negative brush, through the galvanometer, and back to the positive brush to complete the circuit through the armature coil. If the coil is rotated to the position shown in figure 14-3 (C), the generated voltage and the current fall to zero, as in figure 14-3 (A). At this instant the brushes make contact with both bars of the commutator and short-circuit the coil. As the coil moves to the position shown in figure 14-3 (D), an e.m.f. is generated again in the coil but of opposite polarity.

The e.m.f.'s generated in the two sides of the coil shown in figure 14-3 (D), are in the reverse direction to that of the e.m.f.'s shown in figure 14-3 (B). Since the bars of the commutator have rotated with the coil and are connected to opposite brushes, the direction of the flow of current through the galvanometer remains the same. The e.m.f. developed across the brushes is pulsating and unidirectional (in one

direction only), varying twice during each revolution between zero and maximum.

Figure 14-4 is a graph of the pulsating direct e.m.f. for one revolution of a single-loop 2-pole armature. A pulsating direct voltage of this characteristic (called RIPPLE) is unsuitable for most applications. Therefore, in practical generators more coils and more commutator bars are used to produce an output voltage waveform with less ripple.

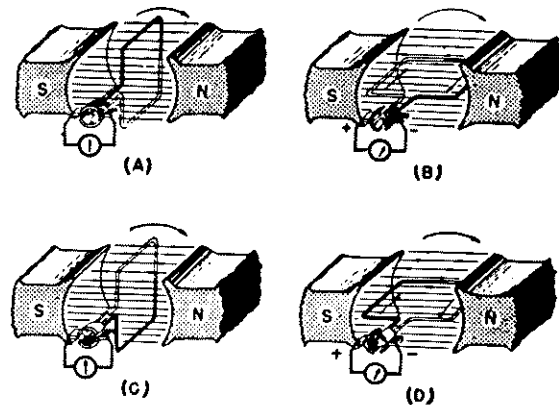


Figure 14-3.—Single-coil generator with commutator.

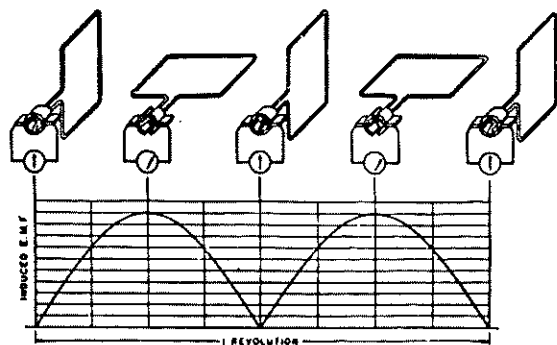


Figure 14-4.—Voltage from a single-coil armature.

EFFECT OF MORE COILS

Figure 14-5 shows the reduction in ripple component of the voltage obtained by the use of two coils instead of one. Since there are now four commutator segments in the commutator and only two brushes, the voltage cannot fall any lower than point A; Therefore, the ripple is limited to the rise and fall between points A and B. By adding still more armature coils, the ripple voltage can be reduced still more.

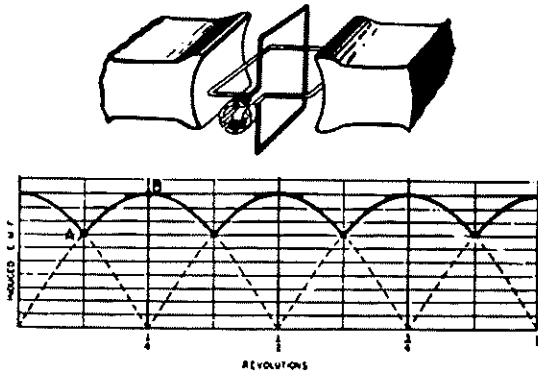


Figure 14-5.—Voltage from a two-coil armature.

GRAMME-RING WINDING

A Gramme-ring winding (fig. 15-6) is formed by winding insulated wire around a hollow iron ring and tapping it at regular intervals to the commutator bars. The portions of the windings on the inside of the ring cut practically no flux and act as connectors for the active portions of the conductors, which lie on the outer surface of the ring. Because only a small fraction of the conductor is used to generate voltage in such a winding, a relatively large amount of copper is required to produce a given voltage. The schematic wiring diagram of a Gramme-ring winding is frequently used as a simplified equivalent circuit for the practical but more complex drum armature wiring diagrams. The Gramme-ring winding is used in this discussion only to simplify the drum winding circuits.

In the 2-pole winding of figure 14-6 (A), there are two parallel paths for armature current between the brushes. One path is through the coils on the left side and the other is through the coils on the right side. The voltage between the brushes is the vector sum of the voltages generated in all the coils of each path. No circulating current flows between the two paths

because the generated voltages in the two paths are equal and in opposition. The polarity of the brushes may be determined by the left-hand rule for generator action. The negative terminal is the one from which electrons flow out to the load; the positive terminal is the one to which the electrons return from the load.

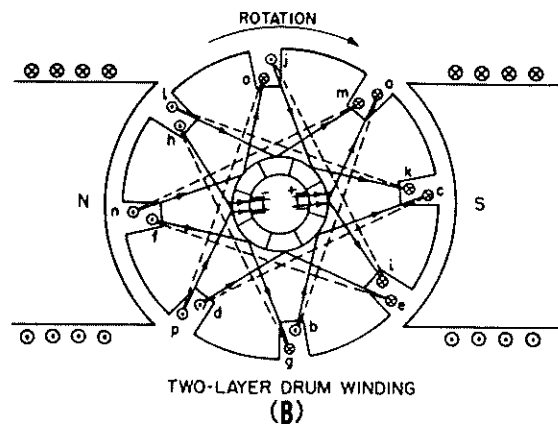
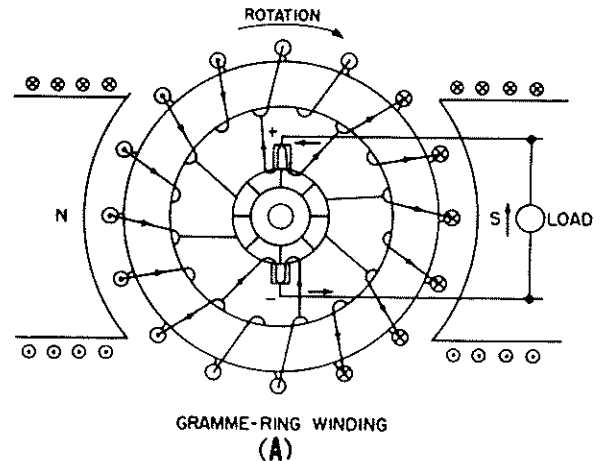


Figure 14-6.—Basic d-c generator armature windings.

DRUM ARMATURE

In the basic drum winding shown in figure 14-6 (B), all the conductors lie in slots near the surface of the armature. The armature conductors are indicated in the figure as circles. Those on the left contain a dot to indicate that the direction of generated voltage is toward the observer; those on the right contain an x to show that the direction of the generated voltage is away from

the observer. The dotted lines connecting the circles represent end connections on the back of the armature between the two halves of each coil. The solid lines between the commutator and the armature conductors represent the end connections on the front of the armature between the coils and commutator segments.

There are 8 coils, 8 slots, and 8 commutator segments in this simplified basic drum winding. One half of a coil lies in the upper portion of a slot and the other half of the coil lies in the lower portion of a slot that is approximately halfway around the armature. This arrangement permits the generated voltages in the two halves of a coil to be a maximum at almost the same instant, because the armature is rotating in a 2-pole field. The polarity of the brushes may be determined by the left-hand rule for generator action. The brushes are shown on the inside of the commutator surface to simplify the drawing. Normally, the brushes contact the outside surface of the commutator.

In drum armatures, with the exception of the coil-end connections, all of the copper is used to generate the e.m.f. The distance between the two sides of a coil is known as the COIL PITCH. This distance should be about the same as the distance between the centers of adjacent poles as mentioned previously.

The following analysis is made for a no-external-load condition. There are two paths for armature current through the drum winding—one through conductors *a, b, c, d, e, f, g, and h*; the other through conductors *i, j, k, l, m, n, o, and p*. The generated voltages in all conductors in the first path are in the same direction—from the positive brush to the negative brush. The generated voltages in all conductors in the second path are also all in the same direction—from the positive brush to the negative brush. The two paths form a closed circuit and the voltages of each path are equal and in opposition with respect to each other. Therefore no circulating current will flow.

Certain similarities exist in the Gramme-ring winding (fig. 14-6 (A)) and the drum winding (fig 14-6 (B)). The generated voltage distribution is the same. The number of paths for load current is the same. In both types, when a brush contacts two segments, a coil is short-circuited. In both types, the brushes are positioned so that only coils that are moving approximately parallel to the field are short-circuited. That is, a coil is short-circuited only at the exact instant that it has no voltage induced in it. Thus, sparking

is minimized. In both types, there are 8 commutator bars and 2 brushes and the armatures are wound for 2-pole fields. Also, in both types there are single-turn coils and 16 active conductors in which the voltage of the machine is generated.

The differences that exist in the two types of armatures are in the position of the brush axis, the method of mounting the coils, and the path for the magnetic field flux. In the Gramme-ring winding the brush axis is perpendicular to the field axis. In the drum winding the brush axis coincides with the field axis. In the Gramme-ring armature the coils are wound on a ring. In the drum type they are preformed and inserted in slots. In the Gramme-ring type the magnetic field crosses the air gap and is confined to the ring. In the drum type the field crosses the air gap and permeates the entire cross section of the armature including the outer slotted portion as well as the inner section. Finally, the end connections form a much higher percentage of the total winding in the Gramme-ring type than in the drum type. It is principally for this reason that Gramme-ring armatures have been replaced by the more efficient drum-type armature.

SIMPLEX LAP WINDING

As mentioned previously, direct-current armatures are generally wound with preformed coils, as shown in figure 14-7. The term "span" is the distance from one winding element of a coil to the other winding element of the same coil and is usually given in terms of the number of slots included between them. A winding element is a coil side consisting of one or more active (face) conductors in series and taped together to form that part of the coil that is inserted in the armature slot. The span of the armature coil should be about equal to the peripheral distance between the centers of adjacent field poles, so that the voltages generated in the two sides of the coil will be in series addition. This distance is called POLE PITCH. When the span of a coil is less than the pole pitch the winding is called a FRACTIONAL-PITCH WINDING. A fractional pitch coil can be as low as 0.8 pole pitch. Fractional pitch coils have reduced e.m.f. because the coil side voltages do not reach their maximum values at the same time. Ordinarily, the reduction in e.m.f. is small. The savings in copper, in shorter end-connections, warrants the loss.

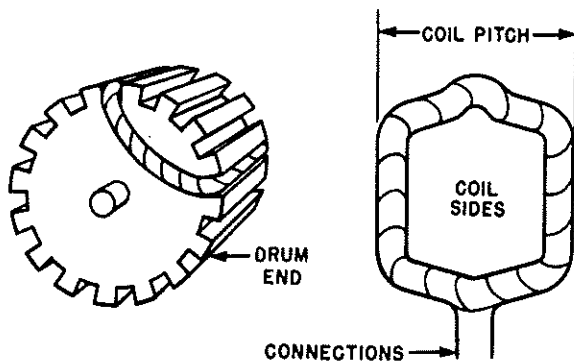


Figure 14-7.—Formed armature coil for 4-pole armature.

Direct-current armature windings are generally 2-layer windings. In this arrangement, the coils are placed on the armature with one side of a coil occupying the top of one slot and its other side occupying the bottom of another slot. The distance between the slots is approximately 1 pole span. Such an arrangement allows the windings to fit readily on the armature with an equal number of coils and slots. Thus each slot contains two layers of conductors in which voltages are generated as the armature rotates through the field. This arrangement is shown in

the 2-layer drum winding of figure 14-6 (B).

A 4-pole simplex-lap winding is shown in figure 14-8. Starting with commutator bar 1, the circuit may be traced through the heavy black coil to the adjacent commutator bar 2. The trace may be continued through successive coils until the entire armature circuit has been traced from one end to the other. Upon reentering the starting commutator bar 1, the trace is completed. Thus, the circuit is seen to be a closed-circuit winding.

There are four groups of coils generating the same voltage between brushes of opposite polarity in the example shown in figure 14-8. One group consists of coils occupying winding spaces 1, 12, 3, 14, 5, 16, 7, 18, 9, and 20. A second group consists of coils occupying winding spaces 11, 22, 13, 24, 15, 26, 17, 28, 19, and 30. A third group consists of coils occupying winding spaces 21, 32, 23, 34, 25, 36, 27, 38, 29, and 40. The fourth group consists of coils occupying winding spaces 31, 42, 33, 2, 35, 4, 37, 6, 39, 8, 41, and 10. These four groups of coils are placed in parallel by connecting the two positive brushes together and the two negative brushes together as indicated in the schematic diagram of figure 14-8 (B). No circulating current flows between these four parallel paths when no load is connected between the positive and negative brushes,

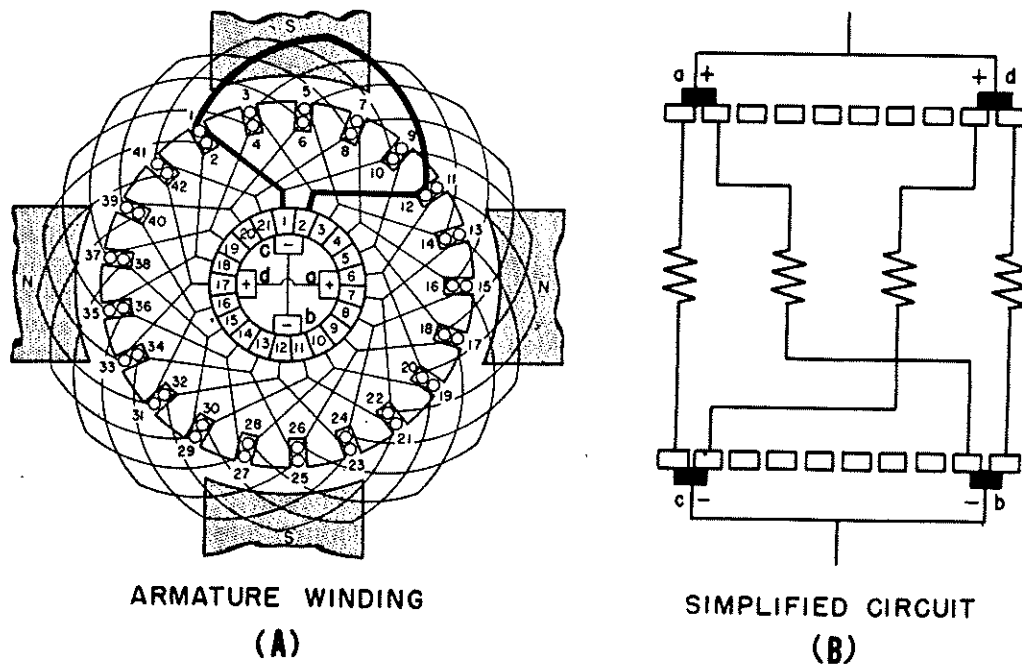


Figure 14-8.—Simplex-lap 4-pole armature winding.

because the voltage of each of the groups is equal and of opposite polarity to the voltages of the other groups.

A simplified schematic of the 4-pole simplex-lap armature winding is shown in figure 14-9. Connecting a load between the positive and negative brushes causes current to flow through the armature in these four paths. The current is distributed equally in the four paths. Thus if the total output current of the armature is 400 amperes, each path through the armature will carry 100 amperes. In this winding there are as many parallel paths for current through the armature as there are poles in the field.

The simplex-lap winding described in this chapter is the simplest type of lap winding. It is identified as a single winding to distinguish it from more complex double and triple lap windings. It is single-reentrant—that is, the winding closes on itself at the end of one complete turn around the armature. This arrangement distinguishes the winding from more complex types that reenter upon themselves after one, two, or three complete turns around the armature. The more complex lap windings are described in the texts that pertain to particular ratings.

The characteristics of the (single) simplex-lap winding may be summarized as follows:

1. There are as many paths for current as there are field poles.

2. There are as many brush positions on the commutator as there are field poles.

3. The two ends of an armature coil connect to adjacent commutator segments.

4. The armature winding forms a continuous closed circuit.

5. The lap armature winding is used for relatively high-current low-voltage loads.

6. The voltage generated between positive and negative brushes is

$$E = \frac{\phi Z N}{10^8}$$

where E is the generated e.m.f. in volts, Z the number of armature face conductors, ϕ the lines of magnetic flux per pole, and N the armature speed in revolutions per second.

A face conductor lies in a slot and generates a voltage as the armature rotates. An armature coil includes one or more turns, each of which consists of two face conductors and their respective end connections. For example, a 4-pole d-c generator with a simplex-lap armature winding having 10^6 lines of magnetic flux per pole, 440 armature conductors, and a speed of 50 revolutions per second (3,000 r.p.m.) has a generated voltage of

$$E = \frac{10^6 \times 440 \times 50}{10^8} = 220 \text{ volts.}$$

If the load current is 1,000 amperes, each armature coil will carry $\frac{1,000}{4}$, or 250 amperes.

SIMPLEX WAVE WINDING

In the single simplex-wave winding (fig. 14-10) groups of coils under similar pairs of poles at any instant are generating equal voltages and are connected in series. This winding is also called a **SERIES WINDING**. Each coil has its ends connected to the commutator bars that are two pole spans apart. This distance is measured around the armature circumference from the center of one field pole to the center of the next pole of like sign. In this example, the distance covered by two pole spans is halfway around the commutator; in a 6-pole machine, two pole spans are one-third the way around; and in an 8-pole machine, one-fourth the way around. In the single simplex-wave winding there are as many coils connected in series between adjacent commutator bars as there are pairs of poles in the field. In this example there are two pairs of poles, so there are two coils in series between adjacent commutator bars. This arrangement

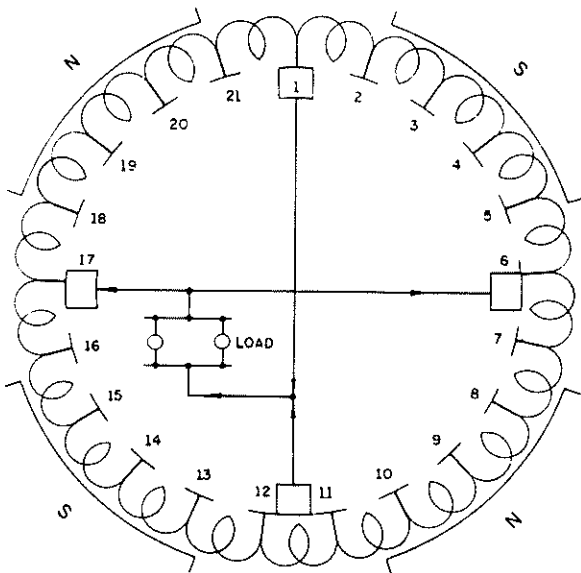


Figure 14-9.—Simplified schematic of simplex-lap 4-pole armature winding.

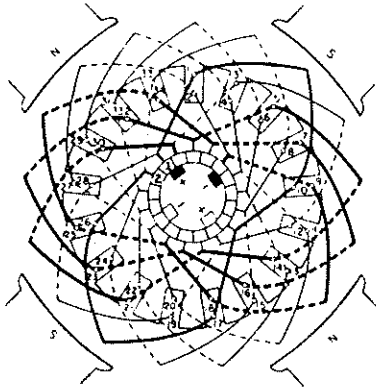


Figure 14-10.—Single simplex-wave winding.

may be seen by starting at segment 1 and tracing through the circuit of the two coils occupying winding spaces 1, 10, 17, and 26, and ending at commutator segment 2.

The single simplex-wave winding is a closed-circuit winding as may be seen by starting with one coil and tracing through the entire armature circuit to complete the trace by ending at the starting position. In the single simplex wave-wound armature there are two paths for current regardless of the number of poles for which it is wound and regardless of the number of brushes. Starting with the upper positive brush, one path includes the armature conductors that occupy winding spaces 1, 10, 17, 26, 33, 8, 15, 24, 31, 6, 13, 22, 29, 4, 11, 20, 27, and 2, returning to the upper negative brush. The other path from the upper positive brush includes the armature conductors that occupy winding spaces 28, 19, 12, 3, 30, 21, 14, 5, 32, 23, 16, 7, 34, 25, 18, and 9, returning to the upper negative brush.

Although four brushes are shown, only two are required. The full voltage of the winding is developed across the upper brushes, and the full voltage is also developed across the lower brushes. The load current divides equally between the two pairs of brushes when they are connected in parallel because the resistance of the two paths through the armature is the same. For example, if the armature has a 20-ampere load at 220 volts the upper brushes alone will

carry 20 amperes at 220 volts. Adding the lower brushes will reduce the current to 10 amperes per brush. If the commutator is designed for four brushes, the removal of one pair will overload the remaining brushes unless the load is halved. However, where commutators are inaccessible, wave windings permit the use of two brush positions irrespective of the number of poles, so that servicing the brushes and commutator is facilitated.

The characteristics of the simplex-wave winding may be summarized as follows:

1. There are two parallel paths irrespective of the number of field poles.
2. There is a minimum of two brush positions irrespective of the number of field poles.
3. The two ends of a coil connect to commutator segments that are two pole spans apart (fig. 15-10).
4. The winding has relatively high voltage and low current.
5. The winding forms a continuous closed circuit.
6. There are as many coils in series between adjacent commutator segments as there are pairs of poles in the field.
7. The voltage generated between positive and negative brushes is

$$E = \frac{\Phi ZNP}{10^8}$$

where P is the number of pairs of field poles and the other symbols are the same as those used in the equation for generated voltage in a simplex-lap winding.

For example, a 6-pole d-c generator having a simplex-wave armature winding, 1.05×10^6 lines of flux per pole, 3,500 armature conductors, and a speed of 10 revolutions per second (600 r.p.m.) has a generated voltage of

$$E = \frac{\Phi ZNP}{10^8} = \frac{1.05 \times 10^6 \times 3,500 \times 10 \times 3}{10^8} = 1,100 \text{ volts.}$$

If the armature supplies 200 amperes to a load, each armature coil will carry $\frac{200}{2} = 100$ amperes.

Armature Losses

There are three losses in every d-c generator armature. These are (1) the I^2R or copper loss in the winding, (2) the eddy current loss

in the core, and (3) the hysteresis loss due to the friction of the revolving magnetic particles in the core.

COPPER LOSSES

The copper loss is the power lost in heat in the windings due to the flow of current through the copper coils. This loss varies directly with the armature resistance and as the square of the armature current. The armature resistance varies with the length of the armature conductors and inversely with their cross-sectional area.

Armature conductor size is based on an allowance of from 300 to 1,200 circular mils per ampere. For example, a 2-pole armature that is required to supply 100 amperes may use a wire size based on 800 circular mils per ampere, or $\frac{100}{2} \times 800 = 40,000$ circular mils. This value corresponds to a No. 4 wire. Very small armature windings may use only 300 circular mils per ampere with a resulting high current density. Large generators (5,000 kw.) require an allowance of 1,200 circular mils per ampere with a resulting low current density in the windings. These variations are the result of the variable nature of the heat-radiating ability of the armature conductors.

Very small round conductors have a much higher ratio of surface to volume than do large round conductors. For example, a 0.1-inch diameter round conductor of a given length has a surface-to-volume ratio of

$$\frac{4\pi D}{\pi D^2}, \text{ or } \frac{4}{0.1} = 40.$$

A 1.0-inch diameter conductor of the same length has a surface-to-volume ratio of $\frac{4}{1}$, or 4. Since the heat-radiating ability of a round conductor varies as the ratio of its surface to volume, the 0.1-inch diameter conductor has $\frac{40}{4}$, or 10 times the heat radiating ability of the 1-inch diameter conductor, other factors being equal.

High-speed generators use a lower circular-mil-per-ampere allowance than low-speed generators because of better cooling. The temperature rise is limited by ventilating ducts, and in some cases by the use of forced ventilation, as in aircraft d-c generators.

The hot resistance of an armature winding is higher than its cold resistance. A 2.5° centigrade increase in temperature of a copper conductor corresponds to an increase in resistance of approximately 1 percent. For example, if the no-load temperature of an armature winding is 20° C. and its full-load temperature is 70° C.,

the increase in resistance is $\frac{70-20}{2.5}$, or 20 percent. Thus, if the no-load resistance is 0.05 ohm between brushes, the hot resistance will be 1.2 x 0.05, or 0.06 ohm. If the full-load armature current is 100 amperes, the full-load armature copper loss will be $(100)^2 \times 0.06$, or 600 watts. The armature copper loss varies more widely with the variation of electrical load on the generator than any other loss occurring in the machine. This is because most generators are constant-potential machines supplying a current output that varies with the electrical load across the brushes. The limiting factor in load on a generator is the allowable current rating of the generator armature.

The armature circuit resistance includes the resistance of the windings between brushes of opposite polarity, the brush contact resistance, and the brush resistance.

EDDY-CURRENT LOSSES

If a d-c generator armature core were made of solid iron (fig. 14-11 (A)) and rotated rapidly in the field, excessive heating would develop even with no-load current in the armature windings. This action would be the result of a generated voltage in the core itself. As the core rotates, it cuts the lines of magnetic field flux at the same time the copper conductors of the armature cut them. Thus, induced currents alternate through the core, first in one direction and then in the other, with accompanying generation of heat.

These induced currents are called EDDY CURRENTS. They are kept to a low value by sectionalizing (laminating) the armature core. For example, if the core is split into two equal parts (fig. 14-11 (B)) and these parts are insulated from each other, the voltage induced in each section of iron is halved and the resistance of the eddy-current paths is doubled (resistance varies inversely with the cross-sectional area). If 10 volts is induced in the core (fig. 14-11 (A)) and the resistance of the path for eddy currents is 1 ohm, the eddy-current loss is $\frac{E^2}{R}$, or $\frac{10^2}{1} = 100$ watts. The voltage in each section (fig. 14-11 (B)) will be $\frac{10}{2}$, or 5 volts, because the length is halved and the resistance of the eddy-current path for each section is 2 ohms. The loss in each section is $\frac{E^2}{R}$, or $\frac{5^2}{2} = 12.5$ watts, and the total

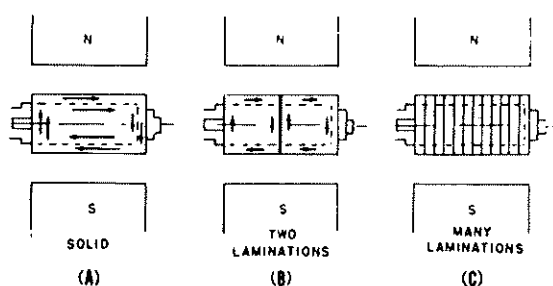


Figure 14-11.—Eddy currents in d-c generator armature cores.

loss in both sections is 12.5×2 , or 25 watts. This value represents one-fourth of the power loss in figure 14-11 (A).

Reducing the thickness of the core to one-half its original value reduces the loss to one-fourth of the original loss. Thus, eddy-current losses vary as the square of the thickness of the core laminations.

If the armature core is sufficiently subdivided into multiple sections or laminations (fig. 14-11 (C)), the eddy-current loss can be reduced to a negligible value. Reducing the thickness of the laminations reduces the magnitude of the induced e.m.f. in each section and increases the resistance of the eddy-current paths. Laminations in small generator armatures are $1/64$ inch thick. The laminations are insulated from each other by a thin coat of lacquer or in some instances simply by the oxidation of the surfaces due to contact with the air while the laminations are being annealed. The insulation need not be high because the voltages induced are very small.

All electrical rotating machines are laminated to reduce eddy-current losses. Transformer cores are laminated for the same reason.

The eddy-current loss is also influenced by speed and flux density. Because the induced voltage, which causes the eddy-currents to flow, varies with the speed and flux density, the power loss, $\frac{E^2}{R}$, varies as the square of the speed and the square of the flux density.

HYSTERESIS LOSS

When an armature revolves in a stationary magnetic field, the magnetic particles of the armature are held in alignment with the field in varying numbers depending upon the strength of the field. If the field is that of a 2-pole generator, these magnetic particles will rotate, with respect to the particles not held in alignment, one complete turn for each revolution of the armature. The rotation of magnetic particles in the mass of iron produces friction and heat.

Heat produced in this manner is identified as magnetic HYSTERESIS LOSS. The hysteresis loss varies with the speed of the armature and the volume of iron. The flux density varies from approximately 50,000 lines per square inch in the armature core to 130,000 lines per square inch in the iron between the bottom of adjacent armature slots (called the TOOTH ROOT). Heat-treated silicon steel having a low hysteresis loss is used in most d-c generator armatures. After the steel has been formed to the proper shape, the laminations are heated to a dull red heat and allowed to cool. This annealing process reduces the hysteresis loss to a low value.

Armature Reaction

Armature reaction in a generator is the effect on the main field of the armature acting as an electromagnet. With no armature current, the field is undistorted, as shown in figure 14-12 (A). This flux is produced entirely by the ampere-turns of the main field windings. The neutral plane AB is perpendicular to the direction of the main field flux. When an armature conductor moves through this plane its path is parallel to the undistorted lines of force and the conductor does not cut through any flux. Hence no voltage is induced in the conductor. The brushes are placed on the commutator so that they short-

circuit coils passing through the neutral plane. With no voltage generated in the coils, no current will flow through the local path formed momentarily between the coils and segments spanned by the brush. Therefore, no sparking at the brushes will result.

When a load is connected across the brushes, armature current flows through the armature conductors, and the armature itself becomes a source of magnetomotive force. The effect of the armature acting as an electromagnet is considered in figure 14-12 (B), with the assumption that the main field coils are deenergized and

full-load current is introduced to the armature circuit from an external source. The currents in the conductors on the left of the neutral plane all carry current toward the observer, and those on the right carry current away from the observer. These directions are the same as those in which the current would flow if it were under the influence of the normal e.m.f. generated in the armature with normal field excitation.

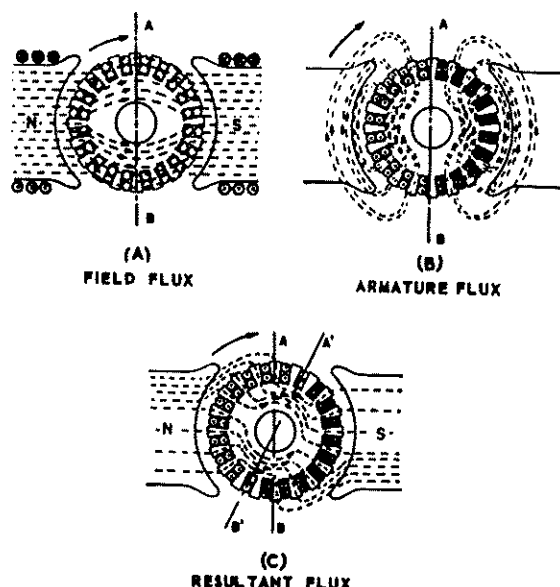


Figure 14-12.—Flux distribution in a d-c generator.

These armature current-carrying conductors establish a magnetomotive force that is perpendicular to the axis of the main field, and in the figure the force acts downward. This magnetizing action of the armature current is called **CROSS MAGNETIZATION** and is present only when current flows through the armature circuit. The amount of cross magnetization produced is proportional to the armature current.

When current flows in both the field and armature circuits, the two resulting magnetomotive forces distort each other. They twist in the direction of rotation of the armature. The mechanical (no load) neutral plane, AB (fig. 14-12 (C)), is now advanced to the electrical (load) neutral plane, A'B'. When armature conductors move through plane A'B' their paths are parallel to the distorted field and the conductors cut no flux, hence no voltage is induced in them. The brushes must therefore be moved on the

commutator to the new neutral plane. They are moved in the direction of armature rotation. The absence of sparking at the commutator indicates correct placement. The amount that the neutral plane shifts is proportional to the load on the generator because the amount of cross-magnetizing magnetomotive force is directly proportional to the armature current.

When the brushes are shifted into the electrical neutral plane A'B' the direction of the armature magnetomotive force is downward and to the left, as shown in figure 14-13 (A), instead of vertically downward. The armature magnetomotive force may now be resolved into two components, as shown in figure 14-13 (B).

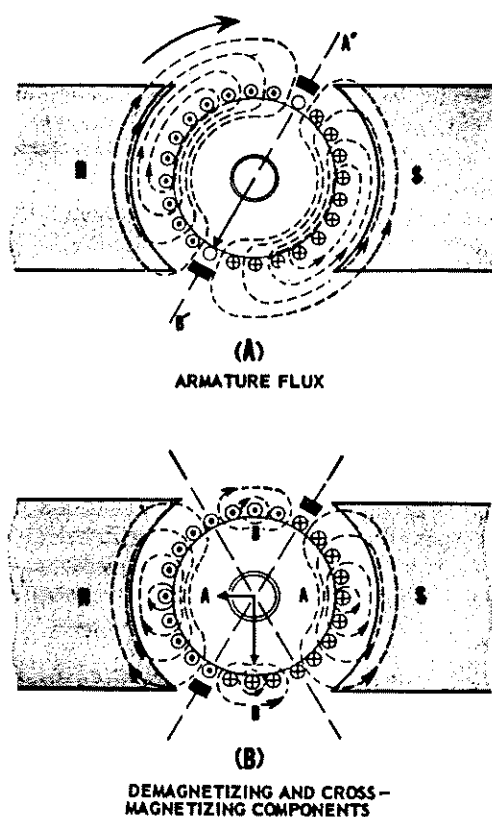


Figure 14-13.—Effect of brush shift on armature reaction.

The conductors included at the top and bottom of the armature within sectors BB produce a magnetomotive force that is directly in opposition to the main field and weakens it. This component is called the **ARMATURE DEMAGNETIZING M.M.F.** The conductors included on the

right and left sides of the armature within sector AA produce a cross-magnetizing m.m.f. at right angles to the main field axis. This cross-magnetizing force tends to distort the field in the direction of rotation. As mentioned previously, the distortion of the main field of the generator is the result of **ARMATURE REACTION**. Armature reaction occurs in the same manner in multipolar machines.

COMPENSATING FOR ARMATURE REACTION

The effects of armature reaction are reduced in d-c machines by the use of (1) high flux density in the pole tips, (2) a compensating winding, and (3) commutation poles.

The cross-sectional area of the pole tips is reduced by building the field poles with laminations having only one tip. These laminations are alternately reversed when the pole core is stacked so that a space is left between alternate

laminations at the pole tips. The reduced cross section of iron at the pole tips increases the flux density so that they become saturated and the cross-magnetizing and demagnetizing forces of the armature will not affect the flux distribution in the pole face to as great an extent as they would at reduced flux densities.

The compensating winding consists of conductors imbedded in the pole faces parallel to the armature conductors. The winding is connected in series with the armature and is arranged so that the ampere-turns are equal in magnitude and opposite in direction to those of the armature. The magnetomotive force of the compensating winding therefore neutralizes the armature magnetomotive force, and armature reaction is practically eliminated. Because of the relatively high cost, compensating windings are ordinarily used only on high-speed and high-voltage generators of large capacity.

Commutating poles are discussed after the description of the process of commutation.

Commutation

Commutation is the process of reversing the current in the individual armature coils and conducting the direct current to the external circuit during the brief interval of time required for each commutator segment to pass under a brush. In figure 14-14, commutation occurs simultaneously in the two coils that are undergoing momentary short circuit by the brushes—coil *B* by the negative brush, and the diametrically opposite coil by the positive brush. As mentioned previously, the brushes are placed on the commutator in a position that short-circuits the coils that are moving through the electrical neutral plane because there is no voltage generated in the coils at the time and no sparking occurs between commutator and brush.

There are two paths for current through the armature winding. If the load current is 100 amperes, each path will contain a current of 50 amperes. Thus each coil on the left side carries 50 amperes in a given direction and each coil on the right side carries a current of 50 amperes in the opposite direction. The reversal of the current in a given coil occurs during the time that particular coil is being short-circuited by a brush. For example, as coil *A* approaches the negative brush it is carrying the full value of 50 amperes which flows through commutator

segment 1 and the left half of the negative brush where it joins 50 amperes from coil *C*.

At the instant shown, the negative brush spans half of segment 1 and half of segment 2. Coil *B* is on short circuit and is moving parallel to the field so that its generated voltage is zero, and no current flows through it. As rotation continues in a clockwise direction the negative brush spans more of segment 1 and less of segment 2. Consider, for example, the interval included between the instant shown in the figure and the instant that the negative brush spans only segment 1. During this time the current in segment 1 increases from 50 to 100 amperes and the current in segment 2 decreases from 50 to 0 amperes. When segment 2 leaves the brush, no current flows from segment 2 to the brush and commutation is complete.

As coil *A* continues into the position of coil *B* the current in *A* decreases to zero. Thus, the current in the coils approaching the brush is reducing to zero during the brief interval of time that it takes for coil *A* to move to the position of coil *B*. During this time the flux collapses around the coil and induces an e.m.f. of self-induction which opposes the decrease of current. Thus, if the e.m.f. of self-induction is not neutralized, the current will not decrease in coil *A*

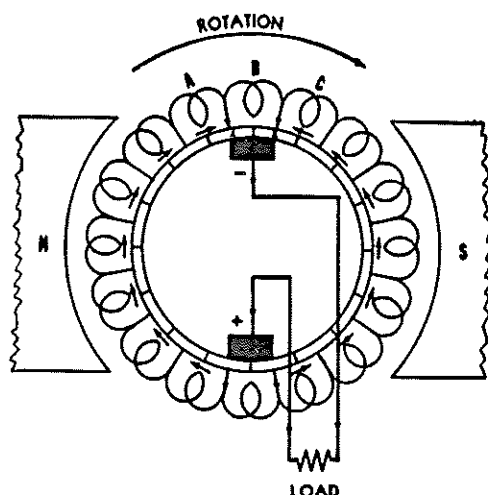


Figure 14-14.—Commutation in a d-c generator.

and the current in the coil lead to segment 1 will not be zero when segment 1 leaves the brush. This delay causes a spark to form between the toe of the brush and the trailing edge of the segment. As the segment breaks contact with the brush, this action burns and pits the commutator.

The reversal of current in the coils takes place very rapidly. For example, in an ordinary 4-pole generator, each coil passes through the process of commutation several thousand times per minute. It is important that commutation be accomplished without sparking to avoid excessive commutator wear.

ADVANCING THE BRUSHES

The e.m.f. of self-induction in the armature coils is caused by the inductance of the coils and the changing current in them and cannot be eliminated. The effects of this e.m.f. can be neutralized however, by introducing into the coil during the process of commutation an e.m.f. that is equal and in opposition to the induced e.m.f. This neutralization can be accomplished by shifting the brushes in the direction of rotation or by using interpoles (commutating poles).

If the brushes are shifted in the direction of rotation until the coils undergoing commutation

cut a small amount of flux from the on-coming main pole, sufficient e.m.f. is induced to neutralize the effect of the self-induced e.m.f. This action allows the coil current to decrease to zero and increase to the desired values in the opposite direction without sparking at the brushes.

The flux necessary to generate the e.m.f. that neutralizes the e.m.f. of self-induction is called the **COMMUTATING FLUX**. This method of reducing sparking at the brushes is satisfactory only under steady-load conditions because the amount of commutating flux required varies with the load and, therefore, the brushes must be shifted with each change in load.

COMMUTATING POLES

Commutating poles, or interpoles, provide the required amount of commutating flux without shifting the brushes from mechanical neutral. They are narrow auxiliary poles located midway between the main poles, as shown in figure 14-2 (F). They establish a flux in the proper direction and of sufficient magnitude to produce satisfactory commutation. They do not contribute to the generated e.m.f. of the armature as a whole because the voltages generated by their fields cancel each other between brushes of opposite polarity.

The interpole magnetomotive force neutralizes that portion of the armature reaction within the zones of commutation and produces the proper flux to generate an e.m.f. in the short-circuited coil that is equal and opposite to the e.m.f. of self-induction. Thus, no sparking occurs at the brushes and "black" commutation indicates the ideal condition. Because both the armature reaction and the self-induced e.m.f. in the commutated coils vary with armature current, the interpole flux varies with the armature current. This condition is obtained by connecting the interpole windings in series with the armature and operating the interpole iron at flux densities well below saturation. The magnetic polarities are such that an interpole always has the same polarity as the adjacent main field pole in the **DIRECTION OF ROTATION**. This relation always exists for d-c generators.

Motor Reaction in a Generator

Whenever a generator delivers current to a load, the load current creates an opposition force that opposes the rotation of the generator armature. An armature conductor is represented in figure 14-15. When the conductor is stationary, no voltage is generated and no current flows; hence, no force acts on the conductor. When the conductor is moved downward and the circuit is completed through an external load, current flows through the conductor in the direction indicated, setting up lines of force around it that have a clockwise direction.

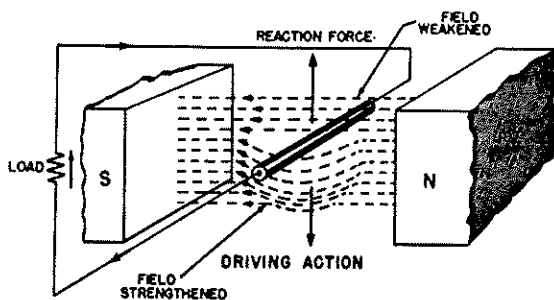


Figure 14-15.—Motor reaction in a generator.

The interaction of the conductor field and the main field of the generator weakens the field above the conductor and strengthens it below the conductor. The field consists of lines that act like stretched rubber bands. Thus, an upward reaction force is produced that acts in opposition to the downward driving force applied to the generator armature. If the current in the conductor increases, the reaction force increases, and more force must be applied to the conductor to keep it from slowing down.

With no armature current, no magnetic reaction exists and the generator input power is low. As the armature current increases, the reaction of each armature conductor against rotation increases and the driving power to maintain the generator armature speed must be increased. If the prime mover driving the generator is a gasoline engine, this effect is accomplished by opening the throttle on the carburetor. If the prime mover is a steam turbine, the main steam-admission valve is opened wider, thus permitting more steam to flow through the turbine.

D-C Generator Characteristics

METHODS OF CONNECTING THE FIELD WINDINGS

Usually d-c generators are classified according to the manner in which the field windings are connected to the armature circuit (fig. 14-16).

A **SEPARATELY EXCITED D-C GENERATOR** is indicated in the simplified schematic diagram of figure 14-16 (A). In this machine the field windings are energized from a separate d-c source other than its own armature.

A **SHUNT GENERATOR** has its field windings connected across the armature in shunt with the load, as shown in figure 14-16 (B). The shunt generator is widely used in industry.

A **SERIES GENERATOR** has its field windings connected in series with the armature and load, as shown in figure 14-16 (B). Series generators are seldom used.

COMPOUND GENERATORS contain both

series and shunt field windings, as shown in figure 14-16 (B). Compound generators are widely used in industry.

FIELD SATURATION CURVES

The strength of the field of a d-c generator depends on the number of ampere-turns in the field windings and the reluctance of the magnetic circuit. The number of turns is generally fixed. Hence, the ampere-turns vary directly with the field current. The generated voltage is directly proportional to the product of the field strength and the speed. Thus, if the field strength is zero or the speed is zero, the generated voltage will be zero. As the current through the field windings increases, the field flux and voltage output will increase. The field strength, however, is not directly proportional to the field current because the reluctance of the magnetic circuit

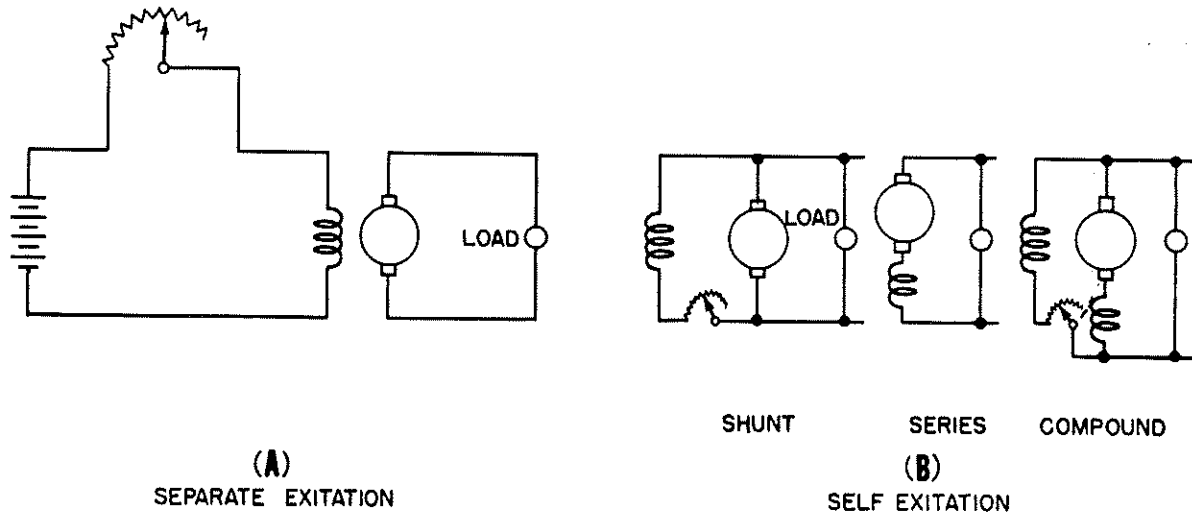


Figure 14-16.—Types of d-c generators.

varies with the degree of magnetization. With increasing flux density in the field and armature iron the permeability decreases, thereby increasing the reluctance of the magnetic circuit and it becomes more difficult to increase the voltage.

Certain operating characteristics of the d-c generator are very closely related to the no-load and the full-load field saturation curves of the machine. The no-load saturation curve is determined with no armature current and the full-load saturation is determined with full-load armature current. The speed is held constant for both curves and the field current is increased in equal steps. The terminal voltage corresponding to each value of field current is plotted and forms the field saturation curves as shown in figure 14-17. The no-load saturation curve is preferably taken with the field separately excited. However, for a shunt or a compound generator these curves can be taken with the machine self-excited because the armature voltage drop due to the shunt field current is negligible.

With a certain field current, OA (fig. 14-17), a no-load e.m.f. of AD volts is generated, but the terminal voltage at full load is AF . The difference, DF , is caused by the armature IR drop and armature reaction. The saturation curves bend to the right at high values of field current and thereby show the tendency of the field iron to saturate. The no-load saturation curve is the magnetization curve of the machine. Because this curve is obtained with no armature current, the observed voltage is the generated e.m.f. of

the machine. At zero field current the e.m.f. is not zero because of the residual flux of the machine. This fact is important because a self-excited generator depends on residual flux to build up its voltage. At low values of field current the voltage varies proportionally, but as the field current increases, the steel portion of the magnetic circuit becomes partly saturated and the voltage increases more slowly.

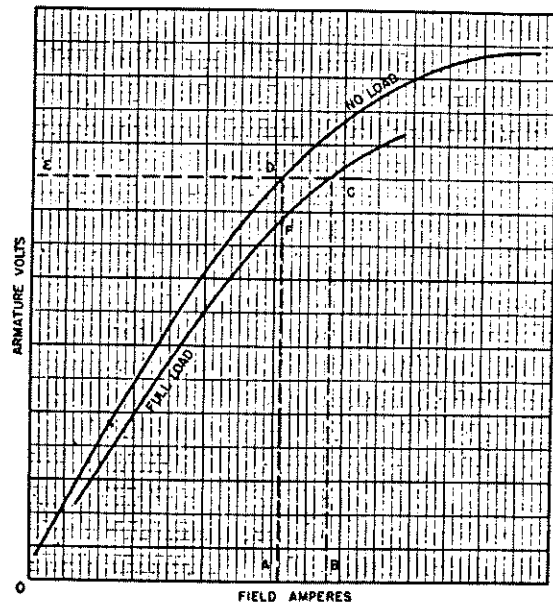


Figure 14-17.—Field saturation curves for d-c generator.

The abrupt bend in the curve is called the **KNEE** of the curve. Shunt generators are designed to operate at a point slightly above the knee so that a slight change in speed does not cause a great change in voltage. Compound generators operate at a lower point in order to avoid the use of a large series field winding.

SHUNT GENERATOR

The shunt generator (fig. 14-16 (B)) has field coils of many turns of small size wire connected in shunt with the armature and load. The armature current is equal to the sum of the field current and the load current. The field current is small compared with the load current and is approximately constant for normal variations in load. Thus, the armature current varies directly with the load. The field flux produced by the field current is normally constant so that the terminal voltage does not vary widely with load change. Hence, the generator is essentially a constant-potential machine that delivers current to the load in accordance with the load demand.

Build Up of Voltage

After the generator is brought up to normal speed, and before any load is connected across the armature, the generator must "build up" its voltage to the rated value (fig. 14-18). A schematic wiring diagram (fig. 14-18 (A)) is shown without load, and with only a few turns of the field coil around one pole indicated for simplicity in tracing the direction of current flow and the polarity of the voltage generated in the armature winding.

Figure 14-18 (B) indicates the field saturation curve for the generator. Line *OA* represents the relation between voltage and current in the field-coil circuit for one value of field-circuit resistance. Line *OA* is called an *IR*-drop curve for the field circuit and is assumed to be a straight line on the basis of constant temperature operation. The field rheostat permits adjustment of the field current through a relatively wide range and is designed so that its resistance is at least equal to that of the field winding.

At start, the generator is brought up to rated speed. The load is not connected. The armature conductors cut the small residual field and gen-

erate about 10 volts across the brushes (point ① on the saturation curve). The left-hand rule for generator action indicates that the generated voltage is applied to the field winding in a direction to supplement the residual field. Ten volts applied across the field circuit will cause approximately 0.07 ampere to flow through the field coils (point ② on the *IR*-drop curve).

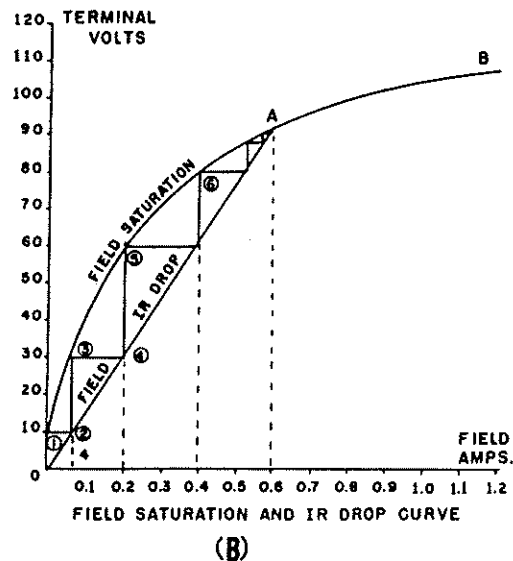
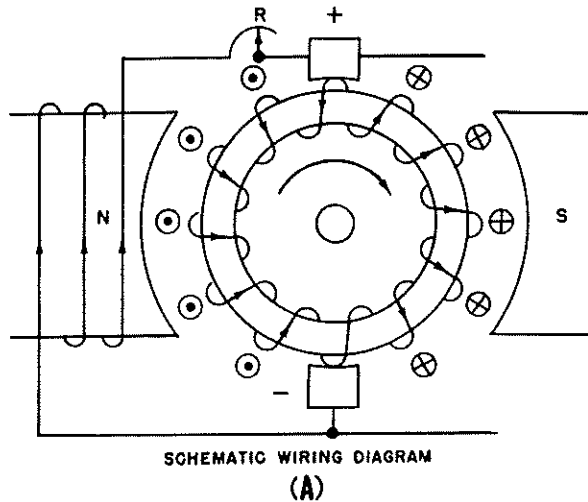


Figure 14-18.—Buildup of voltage of a shunt generator.

This current strengthens the field, and the armature voltage increases to 30 volts, as shown on the field saturation curve (point ③). During

the process of voltage buildup the effect of the armature circuit resistance on the terminal voltage is neglected since the field current is only a small fraction of an ampere. This current flows through the armature and the accompanying IR drop is negligible. A generated voltage of 30 volts applied to the field circuit causes a field current of 0.2 ampere to flow, as shown by the IR -drop curve (point ④). This current in turn increases the field strength and generated voltage in the armature to 60 volts, as indicated on the field saturation curve (point ⑤). This voltage applied to the field causes 0.4 ampere to flow and this action increases the terminal voltage to 80 volts (point ⑥). The rise in voltage continues until the field current has increased to 0.6 ampere and the terminal voltage levels off at 90 volts (point A). No further increase in generated voltage occurs for the given value of field circuit resistance because the amount of field saturation flux produced is enough to generate the voltage required (90 volts) to circulate this current (0.6 ampere) through the field coils. For this condition the resistance of the field circuit is $\frac{90}{0.6}$, or 150 ohms. Field saturation

limits the generated voltage to this value as determined by the setting of the field rheostat.

To increase the shunt generator terminal voltage further, it is necessary to decrease the field circuit resistance. For example, if the terminal voltage is to be increased to 110 volts, the corresponding field current from the saturation curve is 1.2 amperes (point B). The field circuit resistance is now represented by the slope of line OB , or $\frac{110}{1.2} = 91.8$ ohms. Thus, if the field resistance is decreased from 150 ohms to 91.8 ohms, the terminal voltage will increase from 90 volts to 110 volts.

Inherent Regulation of Shunt Generator

Internal changes, both electrical and magnetic, that occur in a generator automatically with load change, give the generator certain typical characteristics by which it may be identified. These internal changes are referred to as the inherent regulation of a generator. At no load, the armature current is equal to the field current. With low armature resistance and low field current there is little armature IR drop, and the generated voltage is equal to the terminal voltage. With load applied, the armature IR

drop increases, but is relatively small compared with the generated voltage. Also the armature reaction voltage loss is small. Therefore, the terminal voltage decreases only slightly provided the speed is maintained at the rated value.

Load is added to a shunt generator by increasing the number of parallel paths across the generator terminals. This action reduces the total load circuit resistance with increased load. Since the terminal voltage is approximately constant, armature current increases directly with the load. Since the shunt field is in a separate circuit it receives only a slightly reduced voltage and its current does not change to any great extent.

Thus, with low armature resistance and a relatively strong field there is only a small variation in terminal voltage between no load and full load.

External Voltage Characteristics

A graph of the variation in terminal voltage with load on a shunt generator is shown in curve A of figure 14-19. This curve shows that the terminal voltage of a shunt generator falls slightly with increase in load from the no-load condition to the full-load condition. It also shows that with heavy overload the terminal voltage falls more rapidly. The shunt field current is reduced and the magnetization of the field falls to a low value. The dotted portion of curve A indicates the way the terminal voltage falls beyond the breakdown point. In large generators the breakdown point occurs at several times rated load current. Generators are not designed to be operated at these large values of load current and will overheat dangerously even at twice the value of full-load current.

Curve B represents the external voltage characteristic of a shunt generator with constant field current for variations in load between zero and approximately 25 percent over the rated load condition. Curve C represents the external voltage characteristic for the same range of load with simulated conditions of zero armature reaction and constant field current. The divergence of curve C from curve D represents the voltage variations resulting from the IR drop in the armature circuit. As mentioned previously, the terminal voltage of the shunt generator is prevented from varying widely with load change by providing it with a (1) low armature resistance, (2) strong main field with low armature

DIRECT-CURRENT GENERATORS

reaction, and (3) separate field circuit in shunt with the armature and load.

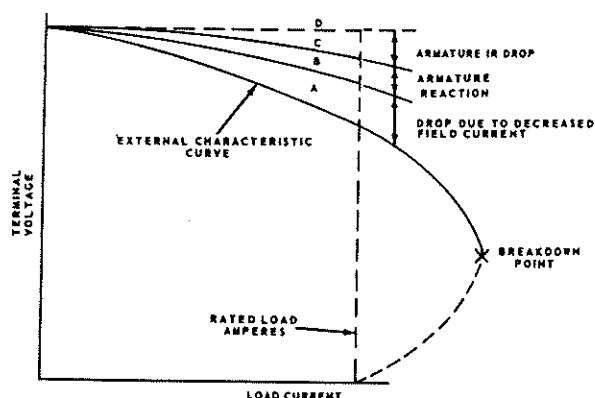


Figure 14-19.—Shunt generator external characteristics.

COMPOUND GENERATOR

Compound generators employ a series field winding in addition to the shunt field winding, as shown in figure 14-16 (B). The series field coils are made of a relatively small number of turns of large copper conductor, either circular or rectangular in cross section, and are connected in series with the armature circuit. These coils are mounted on the same poles on which the shunt field coils are mounted and therefore contribute a magnetomotive force that influences the main field flux of the generator.

Effect of Series Field

If the ampere-turns of the series field act in the same direction as those of the shunt field the combined magnetomotive force is equal to the sum of the series and shunt field components. Load is added to a compound generator in the same manner in which load is added to a shunt generator—by increasing the number of parallel paths across the generator terminals. Thus, the decrease in total load resistance with added load is accompanied by an increase in armature-circuit and series-field circuit current.

The effect of the additive series field is that of increased field flux with increased load. The extent of the increased field flux depends on the degree of saturation of the field iron as determined by the shunt field current. Thus, the terminal voltage of the generator may increase

with load or it may decrease depending upon the influence of the series field coils. This influence is referred to as the degree of compounding.

For example, a **FLAT-COMPOUND** generator is one in which the no-load and full-load voltages have the same value. An **UNDER-COMPOUND** generator is one in which the full-load voltage is less than the no-load value. An **OVER-COMPOUND** generator is one in which the full-load voltage is higher than the no-load value. The way the terminal voltage changes with increasing load depends upon the degree of compounding.

A variable shunt is connected across the series field coils to permit adjustment of the degree of compounding. This shunt is called a **DIVERTER**. Decreasing the diverter resistance increases the amount of armature circuit current that is bypassed around the series field coils, thereby reducing the degree of compounding.

A field rheostat in the shunt field coil circuit permits adjustment of the no-load voltage of the compound generator. The diverter across the series field coils permits adjustment of the full-load voltage.

External Voltage Characteristics

The variation of terminal voltage with load is indicated in the external characteristic curves of figure 14-20. Curve A is the graph of terminal voltage versus armature current for a flat-compound generator. The no-load and full-load voltages are the same. Neither the diverter nor the field rheostat are altered in this test. The speed is maintained constant at the rated value. The hump in the curve is caused by the increased influence of the series ampere-turns on the field iron at half-load when the degree of saturation is reduced and the armature reaction and armature IR drop are approximately half their normal values.

Curve B is the external characteristic of an over-compound generator. As load is added to this machine its terminal voltage increases so that the field load voltage is higher than the no-load value. Such a characteristic might be desirable where the generator is located some distance from the load and the rise in voltage compensates for the voltage loss in the feeder. This action holds the load voltage approximately

constant from no-load to full-load by increasing the generator terminal voltage an amount that is just equal to the voltage drop in the feeder at full load.

Curve C represents the external characteristic for an under-compound generator. The Navy uses a so-called stabilized shunt generator that has a small series field winding of a few turns in the coils to partially compensate for the voltage loss due to armature IR drop and armature reaction. Thus, the external characteristic is almost the same as that of a shunt generator except that the terminal voltage does not fall off quite as rapidly with increased load.

The stabilized shunt generator is the only type of compound generator commonly used in the Navy. This generator is used to supply general lighting and power aboard ship.

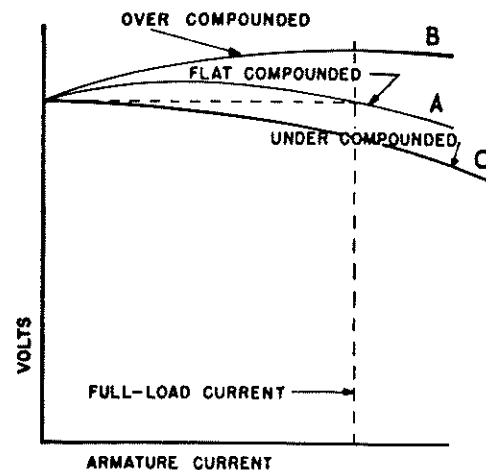


Figure 14-20.—Compound generator external characteristics.

Voltage Regulation

The external characteristic of a generator is sometimes called the **VOLTAGE-REGULATION CURVE** of the machine. The regulation of a generator refers to the **VOLTAGE CHANGE** that takes place when the load is changed. It is usually expressed as the change in voltage from no-load to full-load voltage in percent of full-load voltage. Expressed as a formula,

$$\frac{E_{nL} - E_{fL}}{E_{fL}} \times 100 = \text{percent regulation,}$$

where E_{nL} is the no-load terminal voltage and E_{fL} is the full-load terminal voltage of the generator. For example, the percent regulation of a generator having a no-load voltage of 237 volts and a full-load voltage of 230 volts is

$$\frac{237 - 230}{230} \times 100, \text{ or } 3 \text{ percent.}$$

VOLTAGE CONTROL

Flat-compound generators were formerly used to supply the ship's d-c electric power because they provided a more constant voltage under varying load conditions. Shunt generators are simpler in design and have greater reliability when operating in parallel. The stabilized shunt generator represents a compromise between the two types. As mentioned previously, it has a very light series winding and a slightly

drooping voltage characteristic and is generally used to supply the ship's d-c electric power requirements.

Voltage control is either (1) manual or (2) automatic. In most cases the process involves changing the resistance of the field circuit. By changing field circuit resistance, field current is controlled. Controlling field current permits control of the terminal voltage. Thus, the major difference between various voltage regulator systems is merely the method by which field circuit resistance and current are controlled. When the load changes are infrequent and small, manual control is sufficient to hold the d-c system voltage to the desired value. When the load changes are frequent and large, it may be desirable to employ some form of automatic control.

Inherent voltage regulation should not be confused with voltage control. As described previously, voltage regulation is an internal action occurring within the generator whenever the load changes. Voltage control is a super-imposed action usually by external adjustment. Certain electromechanical devices are used extensively in automatic voltage regulators. These include solenoids, relays, carbon piles, rocking disks, and tilted plates.

Manual Operation

A hand-operated field rheostat (fig. 14-21) connected in series with the shunt field circuit

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provides the simplest method of controlling the terminal voltage of a d-c generator.

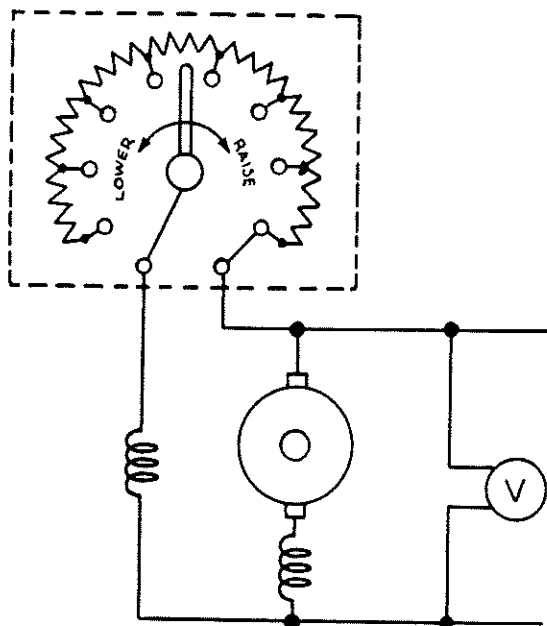


Figure 14-21.—Hand-operated field rheostat.

One form of field rheostat contains tapped resistors with leads to a multiterminal switch. The arm of the switch may be rotated through an arc to make contact with the various resistor taps, thereby varying the amount of resistance in the field circuit. Rotating the arm in the direction of the LOWER arrow increases the resistance and lowers the terminal voltage. Rotating the arm in the direction of the RAISE arrow, decreases the resistance and increases the terminal voltage.

Field rheostats for generators of moderate size employ resistors of alloy wire having a high specific resistance and a low temperature coefficient. These alloys include copper, nickel, manganese, and chromium and are marketed under trade names such as nichrome, advance, manganin, and so forth. Large generator field rheostats use cast-iron grids and a motor-operated switching mechanism.

Automatic Operation

Several types of automatic voltage regulators are used to control the terminal voltage of d-c

generators. One of the earliest types was the vibrating regulator. More recent types include the tilted plate regulator and the rocking disk regulator.

The VIBRATING REGULATOR operates on the principle that an intermittent short circuit applied across the generator field rheostat will cause the terminal voltage of the generator to pulsate within narrow voltage limits and thus it will maintain an average steady value of voltage that is independent of load change. A simplified circuit is shown in figure 14-22.

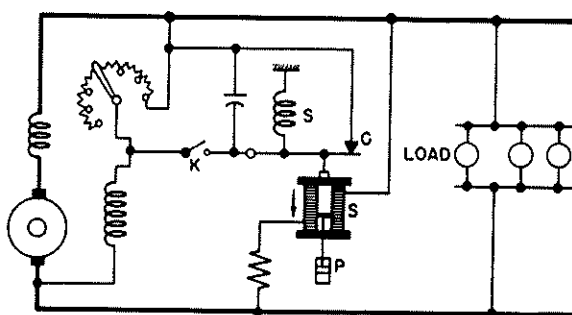


Figure 14-22.—Vibrating type of voltage regulator.

With the generator running at normal speed and switch *K* open, the field rheostat is adjusted so that the terminal voltage is about 60 percent of normal. Solenoid *S* is weak and contacts *C* are held closed by the spring. When *K* is closed, a short circuit is placed across the field rheostat. This action causes the field current to increase and the terminal voltage to rise.

When the terminal voltage rises above a certain critical value, for example 111 volts, the solenoid downward pull exceeds the spring tension and contact *C* opens, thus reinserting the field rheostat in the field circuit and reducing the field current and terminal voltage.

When the terminal voltage falls below a certain critical voltage, for example 109 volts, the solenoid armature contact *C* is closed again by the spring. The field rheostat is now shorted and the terminal voltage starts to rise. The cycle repeats and the action is rapid and continuous. The average voltage of 110 volts is maintained with or without load change.

The dashpot, *P*, provides smoother operation by acting as a damper to prevent hunting. The capacitor across contacts *C* eliminates sparking. Added load causes the field rheostat to be shorted

for a longer period of time and thus the solenoid armature vibrates more slowly. If the load is reduced and the terminal voltage tends to rise, the armature vibrates more rapidly. Thus the regulator holds the terminal voltage to a steady value for any change in load from no load to full load on the generator.

The **TILTED PLATE REGULATOR** (fig. 14-23) consists of two or more stacks of graphite plates mounted on metallic supports at the center of each stack. Each plate is balanced on its fulcrum (the metallic support) at the center. On one end of the stack the plates are separated by mica spacers. On the other end they are sepa-

rated by silver contacts. Before the silver contacts are closed, the path for field circuit current is from graphite plate to graphite plate through the connecting fulcrums at the center of the stack. Between the graphite plates and their supporting fulcrums there exists a certain amount of contact resistance. A weight acting on a lever tilts the plate in a manner that brings the contacts together. A solenoid, which responds to terminal voltage change, tilts the plates in the opposite direction. Bringing the silver contacts together shorts out the resistance of the stack. Opening the silver contacts increases the field circuit resistance. Opening the silver contacts increases the field circuit resistance.

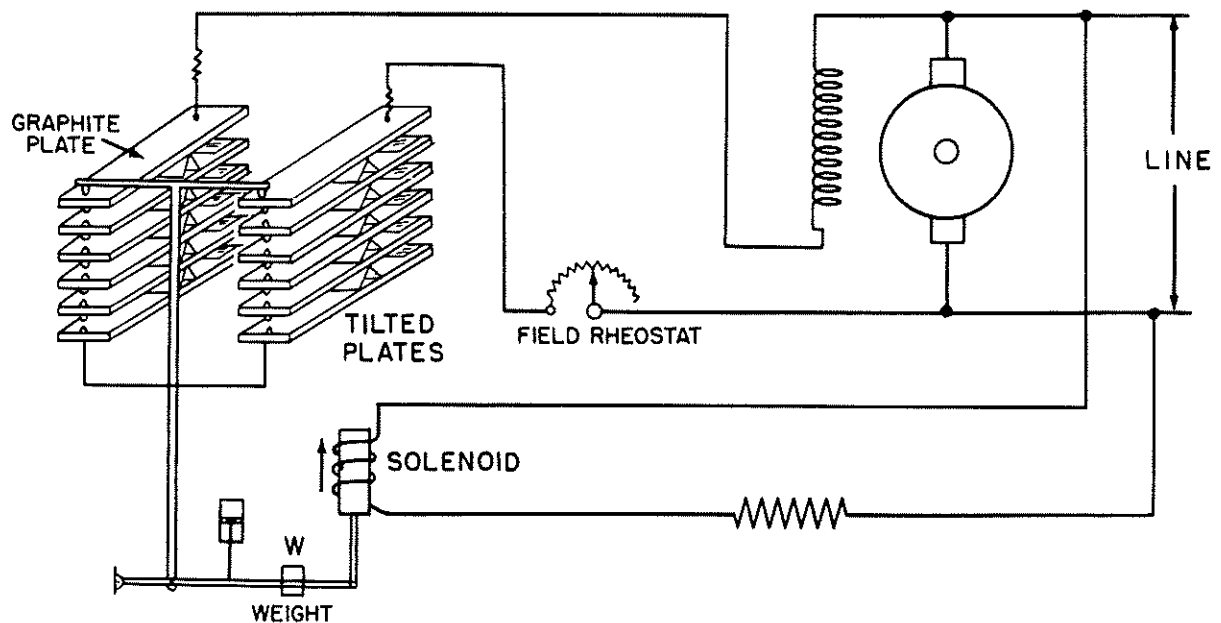


Figure 14-23.—Tilted plate voltage regulator.

The regulator responds to load change and is not designed to overshoot in the manner of the vibrating regulator previously described. For example, at rated voltage the solenoid is in balance with the lever weight and the arm does not move. An increase in load decreases the terminal voltage only slightly because the lever weight immediately overcomes the solenoid and tilts the plates in a direction to lower the resistance, thereby strengthening the field and the generated voltage. This action checks the fall of terminal voltage with load.

The **ROCKING DISK REGULATOR** (fig. 14-24) is another device that is quick acting and

sensitive to slight changes in terminal voltage. It may be designed to be in a constant-motion condition of overshooting the voltage a slight amount through each cycle of operation or it may be operated in a static condition in which load change alone causes it to operate.

A spring presses the rocking disk against the flat surface of a silver-plated commutator, the segments of which connect to taps on the field circuit resistors. The disk has a carbon shoe which makes contact with the segments one at a time from top to bottom as the disk is rocked downward. A small range of motion of the spring is converted into a long range of motion of the

contact point of the carbon shoe with the various commutator segments. The lever weight tends to rock the disk downward. The solenoid tends to rock the disk upward. For a constant load on the generator, the lever weight and the solenoid are in a state of balance. Thus, the shoe is in contact with one commutator segment, and a portion of the field resistors is short-circuited.

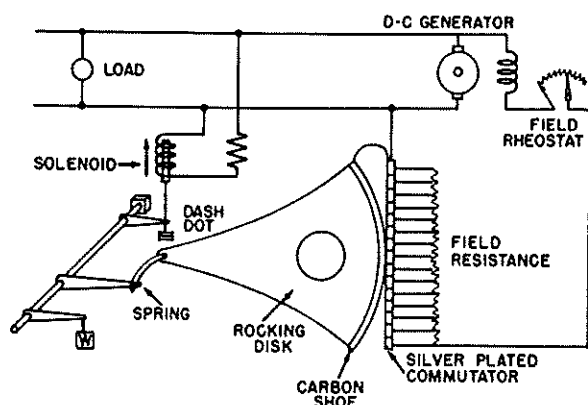


Figure 14-24.—Rocking disk voltage regulator.

When the load on the generator increases, the terminal voltage of the generator starts to fall. The solenoid is weakened and the weight

rocks the disk downward, thus short-circuiting more of the field resistors and increasing the generated voltage. The decrease in terminal voltage is almost instantly checked by the increase in field strength and generated voltage, and the weight is now in balance with the solenoid at a new position where the disk contacts a commutator segment nearer the lower end of its travel.

A decrease in load causes the terminal voltage to start to rise and this strengthens the solenoid. Thus the disk rocks in an upward direction and more resistance is inserted in the field circuit, with accompanying decrease in field strength and generated voltage.

The decrease in generated voltage checks the rise in terminal voltage. For example, at one load the generated voltage is 120 volts, the internal voltage loss is 10 volts, and the terminal voltage is $120 - 10$, or 110 volts. With decrease in load the internal voltage loss might decrease to 5 volts, and without automatic regulation the terminal voltage would increase to $120 - 5$, or 115 volts. However, with automatic regulation the terminal voltage momentarily rises to 111 volts and the regulator causes the generated voltage to fall from 120 volts to $111 + 5$, or 116 volts, and to become stable at 115 volts when the terminal voltage is again $115 - 5$, or 110 volts.

Regulators for Variable-Speed Generators

VIBRATOR-TYPE REGULATOR

If the speed of a shunt generator varies the output voltage will vary. In cars, trucks, small boats, and some aircraft, the generator is usually driven from the main source of power, which may be a variable-speed internal-combustion engine. If the generator is of the shunt type, a 3-unit regulator is often employed. One unit consists of a vibrating voltage regulator that places an intermittent short-circuit across a resistor in series with the field. This action is similar to the vibrating-type voltage regulator described earlier in this chapter. The second unit is a current limiter that limits the output current to a value determined by the rating of the generator. The three-unit regulator (fig. 14-25) is designed for use in a power system

employing a battery as an auxiliary power supply. The third unit in the regulator is a reverse-current cutout that prevents the battery from motorizing the generator at low speeds by disconnecting the battery from the generator. If the voltage of the generator falls below that of the battery, the battery will discharge through the generator armature; thereby tending to drive the generator as a motor. This action is called "motorizing" the generator, and unless it is prevented, will discharge the battery in a short time.

The action of vibrating contact C1 in the voltage-regulator unit (fig. 14-25) places an intermittent short circuit across R1 and L2. When the generator is not operating, spring S1 holds C1 closed. C2 is also closed by S2, and the shunt field is connected directly across the armature.

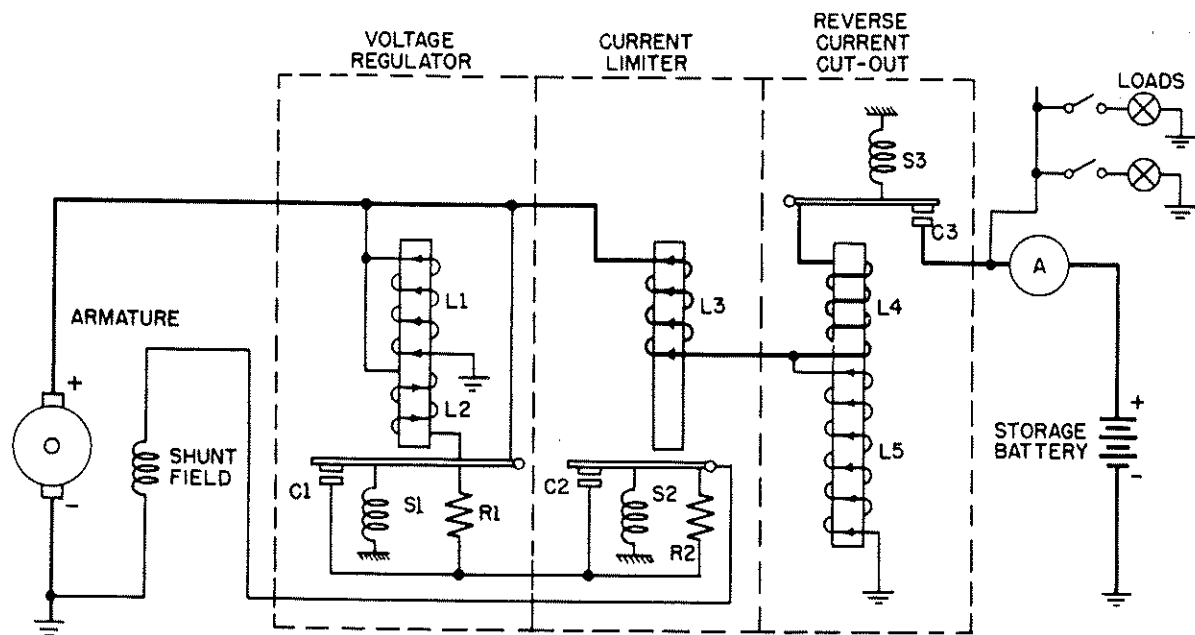


Figure 14-25.—Regulator for variable-speed generator.

When the generator is started, its terminal voltage will rise as the generator comes up to speed, and the armature will apply the field with current through closed contacts C2 and C1.

As the terminal voltage rises, the current flow through L1 increases and the iron becomes more strongly magnetized. At a certain speed and voltage, when the magnetic attraction on the movable arm becomes strong enough to overcome the tension of spring S1, contact points C1 are separated. The field current now flows through R1 and L2. Because resistance is added to the field circuit, the field is momentarily weakened and the rise in terminal voltage is checked. Additionally, because the L2 winding is opposed to the L1 winding, the magnetic pull of L1 against S1 is partially neutralized, and spring S1 closes contact C1. R1 and L2 are again shorted out of the circuit, the field current again increases, the output voltage increases, and C1 is opened because of the action of L1. The cycle of events occurs very rapidly, many times per second. The terminal voltage of the generator thus varies slightly but rapidly above and below an average value determined by the tension of spring S1, which may be adjusted.

The purpose of the vibrator-type current limiter is to limit the output current of the generator automatically to its maximum rated value

in order to protect the generator. As shown in figure 14-25, L3 is in series with the main line and load. Thus, the amount of current flowing in the line determines when C2 will be opened and R2 placed in series with the generator field. By contrast, the voltage regulator is actuated by line voltage, whereas the current limiter is actuated by line current. Spring S2 holds contact C2 closed until the current through the main line and L3 exceeds a certain value, as determined by the tension of spring S2, and causes C2 to be opened. The increase in current is due to an increase in load. This action inserts R2 into the field circuit of the generator and decreases the field current and the generated voltage. When the generated voltage is decreased, the generator current is reduced. The core of L3 is partly demagnetized, and the spring closes the contact points. This causes the generator voltage and current to rise until the current reaches a value sufficient to start the cycle again. A certain minimum value of load current is necessary to cause the current limiter to vibrate.

The purpose of the reverse-current cutout relay (fig. 14-25) is to disconnect the battery automatically from the generator whenever the generator voltage is less than the battery voltage. If this device were not used in the generator

circuit, an especially harmful action would occur if the engine were shut off. The battery would discharge through the generator. This would tend to make the generator operate as a motor, but because the generator is coupled to the engine it could not rotate such a heavy load. Under this condition, the generator winding may be severely damaged by excessive current.

There are two windings, L_4 and L_5 , on the soft-iron core. The current winding, L_4 , consisting of a few turns of heavy wire, is in series with the line and carries the entire line current. The voltage winding, L_5 , consisting of a large number of turns of fine wire, is shunted across the generator terminals.

When the generator is not operating, the contacts, C3, are held open by spring S3. As the generator voltage builds up, L5 magnetizes the iron core. When the current (as a result of the generated voltage) produces sufficient magnetism in the iron core, contact C3 is closed, as shown. The battery then receives a charging current. The coil spring, S3, is so adjusted that the voltage winding will not close the contact points until the voltage of the generator is in excess of the normal voltage of the battery. The charging current passing through L4 aids the current in L5 in holding the contacts tightly closed. Unlike C1 and C2, contacts C3 do not vibrate. When the generator slows down, or for any other cause the generator voltage decreases to a certain value below that of the battery, the current reverses through L4 and the ampere-turns of L4 oppose those of L5. Thus, a momentary discharge current from the battery reduces the magnetism of the core and C3 is opened, thereby preventing the battery from discharging into the generator and motorizing it. C3 will not close again until the generator terminal voltage exceeds that of the battery by a predetermined value.

CARBON-PILE TYPE REGULATOR

The carbon-pile voltage regulator is the type most commonly used in naval aircraft. Its essential parts are shown in figure 14-26. A stack of carbon washers, the "pile," is in series with the shunt field. The resistance of the pile, and thus field current, depends on the mechanical pressure applied to the pile by the wafer spring which acts through the movable iron armature. In a steady-state condition, the magnetic force of the potential coil acts to pull the iron armature away from the pile. This force is balanced by the spring. When a change in line voltage occurs, due to a change in generator speed or load, the potential coil current also changes. Its magnetic strength must also change. As a result, the spring pressure on the carbon pile is INCREASED by a drop in line voltage, and DECREASED by a rise in line voltage. The resultant change in shunt field current will raise or lower the generator output voltage as needed. Variations in voltage characteristics from bench adjustment and aircraft installation may be adjusted by the rheostat, which controls the potential coil current.

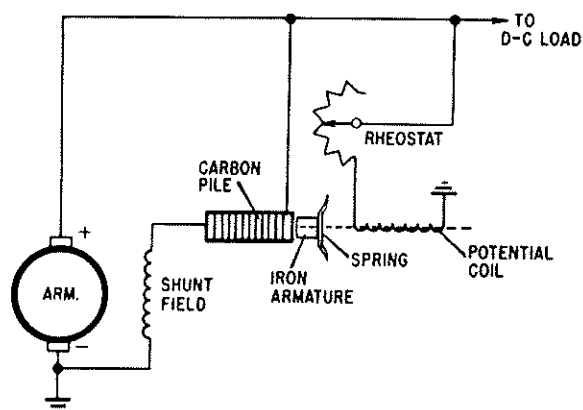


Figure 14-26.—Carbon-pile regulator.

Parallel Operation

Electric power aboard ships may be supplied by more than one generator. When two or more generators are sharing a common load, they are said to be operating in parallel. The generators may be located in different parts of the ship, but are connected to the common load through the ship's power distribution system.

There are a number of reasons for operating generators in parallel. First, the number of generators used may be selected in accordance with the load demand. Thus, by operating each generator as near as possible at its rated capacity, maximum efficiency is achieved. Also, disabled or faulty generators may be taken off

the line without interrupting normal operations.

In naval vessels that are provided with d-c electric power systems, the lighting circuits are designed to operate on 115 volts while most motors and other relatively large power-consuming devices are designed to operate on 230 volts. To avoid the use of separate generators for lighting and for power, a 3-wire generator is used that supplies both types of circuits simultaneously. The 3-wire generator is similar to a 2-wire generator except that the armature winding is tapped at points 180 electrical degrees (1-pole span) apart and these are brought out to slip rings on the back of the armature. These rings are connected by means of brushes to a reactance coil. The center tap of the coil connects with the neutral, or third, wire of the 3-wire system.

The reactance coil (or balance coil) provides a method of establishing the potential of the neutral wire, which must be 115 volts positive with respect to one of the outer wires and 115

volts negative with respect to the other. Alternating current is produced in the armature of the d-c generator; and this is taken from the machine through the sliprings to which the balance coil is attached. The action of the alternating current in the balance coil is similar to that occurring in the primary winding of a single-phase transformer. That is, the potential of the center point on the balance coil is at the electrical center of the total voltage generated by the machine. Hence, this point can serve as the neutral, or center, between the positive and negative brushes. The neutral current passes through a portion of the balance coil, which has low resistance to direct current.

The connections for operating stabilized shunt generators in parallel are shown in figure 14-27. Each generator develops 230 volts across the two outside (positive and negative) leads, and 115 volts across either outside leads and neutral. Usually one ammeter and one voltmeter are provided on each generator panel.

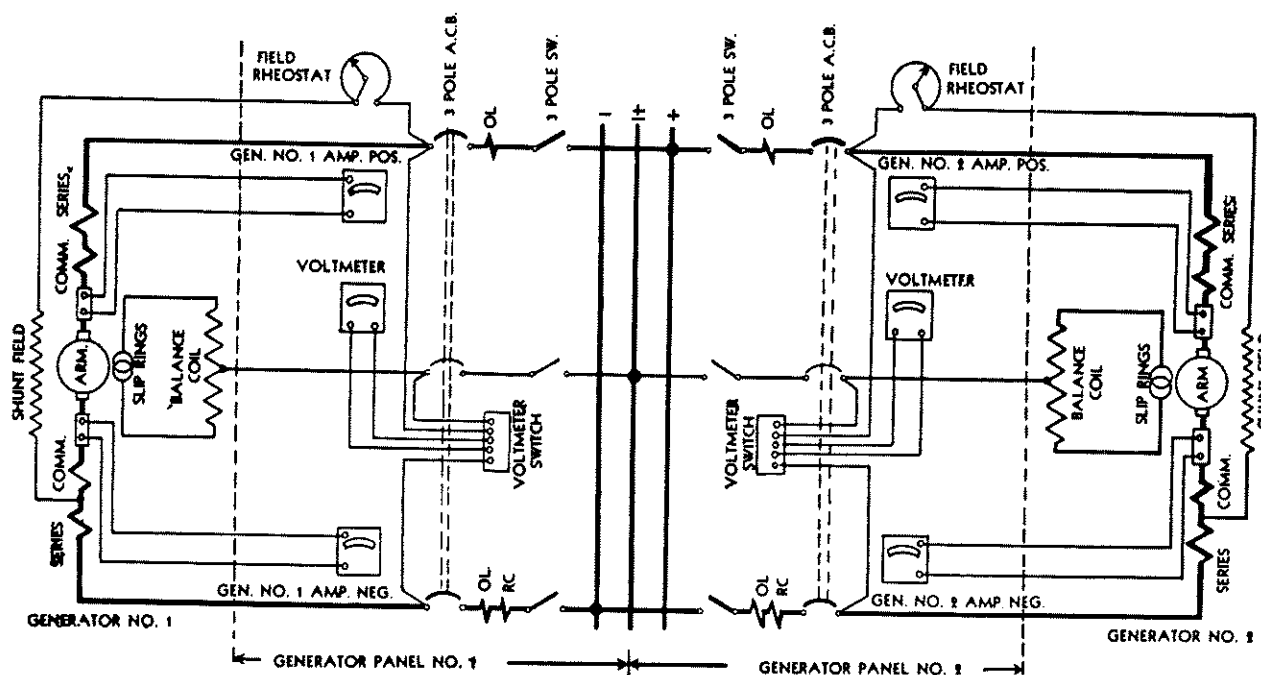


Figure 14-27.—Parallel operation of d-c generators.

Assume that generator No. 1 is supplying the load and it is desired to put generator No. 2 in service. The procedure for paralleling the d-c generators is as follows:

1. The brush rigging and armature of the incoming generator should be inspected for loose gear, and the field rheostat should be adjusted to the lowest voltage position.

DIRECT-CURRENT GENERATORS

2. The prime mover of the incoming generator (No. 2) is brought up to rated speed.

3. The voltage of the incoming machine is adjusted to about 2 volts higher than the bus voltage.

4. Closing the circuit breaker and switch places the generator in parallel with generator No. 1. The ammeter will indicate that generator No. 2 is now carrying a small portion of the load.

5. The field of generator No. 2 is strengthened until the load which it supplies is the proper value. At the same time the field of generator No. 1 should be weakened to maintain the normal voltage.

The procedure for removing a generator from its parallel connection with another is as follows:

1. The field of the generator being secured

is weakened at the same time the field of the remaining generator is strengthened until the load on the outgoing machine is about 5 percent of the rated load current.

2. The circuit breaker is tripped and the switch is opened.

TWO-WIRE D-C SYSTEM

The two-wire d-c system is used for d-c power supply on naval aircraft. On multiengine aircraft, the d-c generators are normally operated in parallel. Figure 15-28 is a schematic of the main parts of a typical aircraft d-c power system. Both generators are connected to the main bus, or common load, through their respective reverse-current cutout relays.

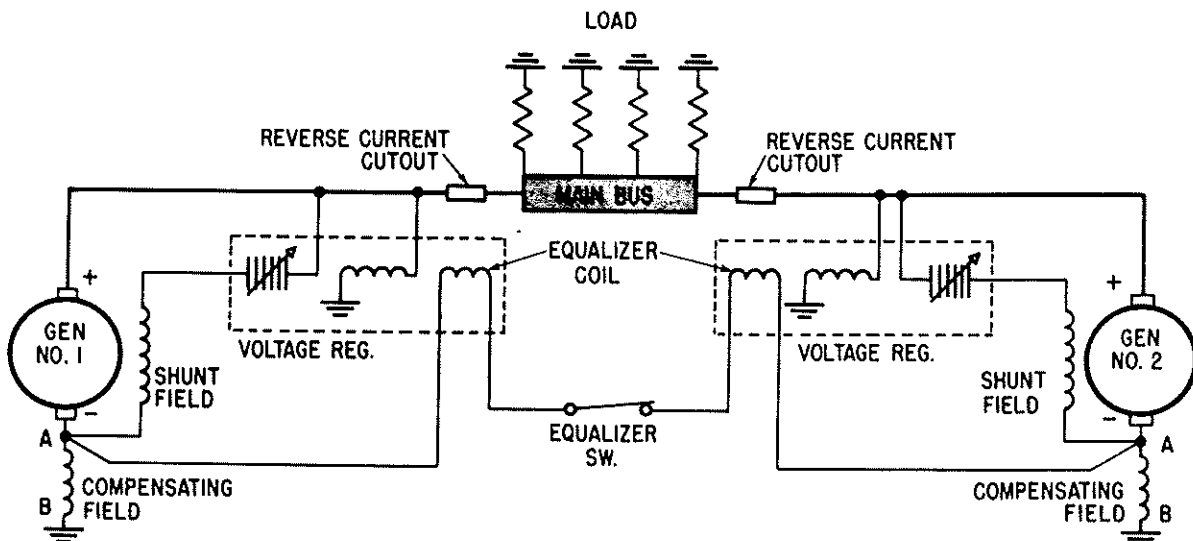


Figure 14-28.—Aircraft d-c power system.

The voltage regulators for aircraft d-c generators are designed and adjusted to permit a slight drooping characteristic. That is, the voltage regulators will permit the terminal voltage of their respective generators to decrease slightly as the bus load is increased. The amount of droop of two or more generators may not be equal, due to internal differences in the generators or adjustment of their regulators. In such cases, one generator will assume more load than the other, as loads are added to the bus.

To assure that the generators will carry equal loads, an automatic load balancing circuit is built into the regulator system. It is referred to as the equalizer. As shown in figure 14-28, the equalizer circuit consists essentially of two equalizer coils and an equalizer switch, all in series, connected between point A in generator No. 1 and point A on generator No. 2. Current through the equalizer circuit flows only when the voltage drops across the compensating fields A-B are unequal. This would be the case

when the generators are supplying unequal shares of the total load. The equalizer coils either aid or oppose the regulator potential coils, depending on the DIRECTION of equalizer current. When one generator takes a greater share of the load than the other, the equalizer coil in its regulator will AID the potential coil. This will cause carbon pile decompression, more resistance and less current in the shunt field, less generated voltage, and consequently a decrease

in load. The other generator's equalizer coil will OPPOSE its potential coil, increase its shunt field current, raise its generated voltage, and thus cause the generator to assume more of the load.

When only one generator is being operated, the equalizer switch is used to open the equalizer circuit. Otherwise, current would flow from the active generator through the dead generator's compensating field and equalizer coil.

QUIZ

1. A d-c generator is a rotating machine that converts
 - a. electrical energy to mechanical energy
 - b. mechanical energy to electrical energy
 - c. low mechanical energy to a higher level of mechanical energy
 - d. low electrical energy to a higher level of electrical energy
2. Commutator segments are insulated from each other by
 - a. small strips of wood
 - b. a rubber insert
 - c. laminated varnish
 - d. sheet mica
3. The brushes that carry the current from the commutator to the external circuit are made of
 - a. carbon and lead
 - b. carbon and graphite
 - c. graphite and lead
 - d. graphite and zinc
4. The heat-radiating ability of very small armature conductors, as compared to large armature conductors, is
 - a. the same
 - b. higher
 - c. lower
 - d. there is no relation
5. The degree that the neutral plane of a generator will shift under load is
 - a. inversely proportional to the load
 - b. proportional to the load
 - c. always less than proportional to the load
 - d. independent of the load
6. D-c generators are classified according to the manner in which
 - a. they are used
 - b. the field windings are connected to the load
 - c. the armature circuit is connected to the load
 - d. the field windings are connected to the armature circuit
7. The only type of compound generator commonly used in the Navy is the
 - a. over compounded
 - b. flat compounded
 - c. stabilized shunt
 - d. cumulative compounded
8. On one end of the tilted plate regulator the graphite plates are separated by mica spacers, while on the other end they are separated by
 - a. platinum contacts
 - b. silver contacts
 - c. zinc contacts
 - d. a carbon shoe
9. In the rocking disk regulator, when the terminal voltage of the generator starts to fall, the disk movement
 - a. opens the circuit to the solenoid
 - b. short-circuits more of the resistors
 - c. short-circuits less of the resistors
 - d. completes the circuit to the solenoid
10. The 3-wire generator is similar to the 2-wire generator except that the armature winding is tapped at
 - a. 30 mechanical degrees
 - b. 90 electrical degrees
 - c. 180 electrical degrees
 - d. 30 electrical degrees
11. The name given to the mechanical power source used to turn the armature of a d-c generator is the
 - a. motor driver
 - b. machine driver
 - c. prime mover
 - d. rotor
12. Flashover between the commutator segments in a high-voltage d-c generator is prevented by
 - a. reducing the number of segments
 - b. increasing the number of segments
 - c. reducing the number of field coils
 - d. increasing the number of field coils

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13. The distance between the two sides of a coil in a d-c generator armature is called
 - a. coil pitch
 - b. commutator pitch
 - c. pole span
 - d. pole pitch
14. The effects of armature reaction in a generator are reduced by the use of
 - a. commutating windings
 - b. interpoles
 - c. commutating windings and interpoles
 - d. compensating windings and commutating poles
15. The need for shifting the brushes of a d-c generator as its load changes has been eliminated by the use of
 - a. interpoles
 - b. commutating poles
 - c. compensating windings
 - d. larger brushes
16. A shunt generator will build up to full terminal voltage with no external load connected to it due to
 - a. the large conductors used in the armature
 - b. motor action of the generator
 - c. interpoles
 - d. self-excitation
17. The percent regulation of a generator having a no-load e.m.f. of 220 volts and a full-load e.m.f. of 215 volts is approximately
 - a. 3%
 - b. 45%
 - c. 0.02%
 - d. 2%
18. The purpose of the vibrator-type current limiter is to automatically limit the output current of the generator to its
 - a. preset value
 - b. minimum rated value
 - c. maximum rated value
 - d. saturation point
19. The main differences between shipboard d-c generators and aircraft d-c generators are
 - a. size, rating, and appearance
 - b. size, appearance, and function
 - c. size and rating only
 - d. appearance, rating, and function
20. The part of a d-c generator into which the working voltage is induced is the
 - a. yoke
 - b. field poles
 - c. armature
 - d. commutator
21. Power lost in heat in the windings due to the flow of current through the copper is known as
 - a. eddy current loss
 - b. hysteresis loss
 - c. copper loss
 - d. none are correct
22. Compensating windings are imbedded in the pole faces parallel to the armature conductors and are electrically connected with the armature windings in
 - a. parallel
 - b. series-parallel
 - c. series
 - d. numbers equal to the number of armature conductors
23. As armature current of a generator increases, motor reaction force
 - a. decreases
 - b. remains the same
 - c. increases
 - d. has no relation to armature current
24. The small variable shunt connected across the series field coils, to permit adjustment of the degree of compounding, is a
 - a. diverter
 - b. divider
 - c. resistor
 - d. rheostat
25. The major difference between various voltage regulator systems is merely the method by which
 - a. field circuit resistance and current are controlled
 - b. armature circuit resistance is controlled
 - c. load circuit resistance is controlled
 - d. armature current and load resistance are controlled
26. In the rocking disk regulator (fig. 14-24), when the terminal voltage of the generator starts to fall, the solenoid is weakened and the weight rocks the disk
 - a. upward
 - b. to the left
 - c. to the right
 - d. downward
27. In the carbon-pile type regulator, the mechanical pressure on the carbon pile is applied by the
 - a. wafer spring
 - b. potential coil
 - c. iron core of the potential coil
 - d. rheostat

CHAPTER 15

DIRECT-CURRENT MOTORS

The construction of a d-c motor is essentially the same as that of a d-c generator. The d-c generator converts mechanical energy into electrical energy, and the d-c motor converts the electrical energy back into mechanical energy. A d-c generator may be made to function as a motor by applying a suitable source of direct voltage across the normal output electrical terminals.

There are various types of d-c motors, depending on the way the field coils are connected. Each has characteristics that are advantageous under given load conditions.

SHUNT MOTORS have the field coils connected in parallel with the armature circuit. This type of motor, with constant potential applied, develops variable torque at an essentially constant speed, even under changing load conditions. Such loads are found in machineshop drives. They include lathes, milling machines, drills, planers, shapers, and so forth.

SERIES MOTORS have the field coils connected in series with the armature circuit. This type of motor, with constant potential applied, develops variable torque but its speed varies widely under changing load conditions. That is, the speed is low under heavy loads, but becomes excessively high under light loads. Series motors are commonly used to drive electric cranes, hoists, winches, and certain types of vehicles (for example, electric trucks). Series motors are used extensively to start internal combustion engines.

COMPOUND MOTORS have one set of field coils in parallel with the armature circuit, and another set of field coils in series with the armature circuit. This type of motor is a compromise between shunt and series motors. It develops an increased starting torque over that of the shunt motor, and has less variation in speed than the series motor. Shunt, series, and compound motors are all d-c motors designed to operate from constant-potential variable-current d-c sources.

STABILIZED SHUNT MOTORS have a light series winding in addition to the shunt field. The action is similar to ordinary shunt motors except that stabilized shunt motors have less field iron and are lighter in weight. Without the stabilizing series field, they have the characteristics of a shunt motor with a strong field and low armature resistance.

Schematic diagrams of the four basic types of d-c motors are shown in figure 15-1.

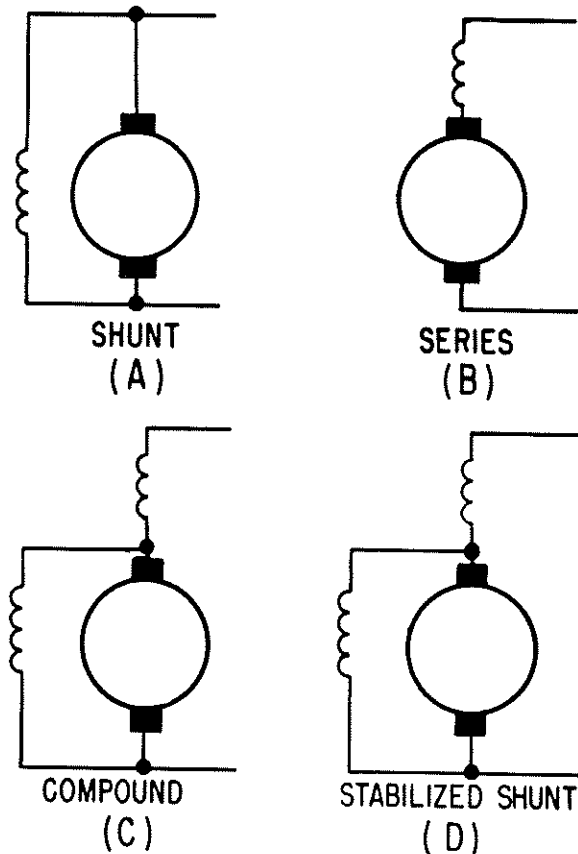


Figure 15-1.—Schematic diagrams of four types of d-c motors.

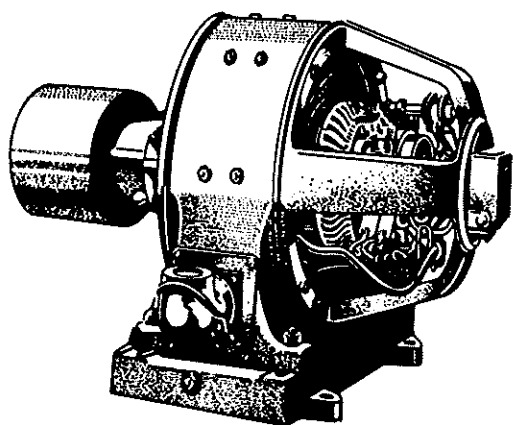
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Direct-current motors may also be classified in other ways. For example, they may be classified according to the degree of enclosure, such as OPEN (fig. 15-2 (A)), DRIP-PROOF (fig. 15-2 (B)), ENCLOSED (fig. 15-2 (C)), and so forth.

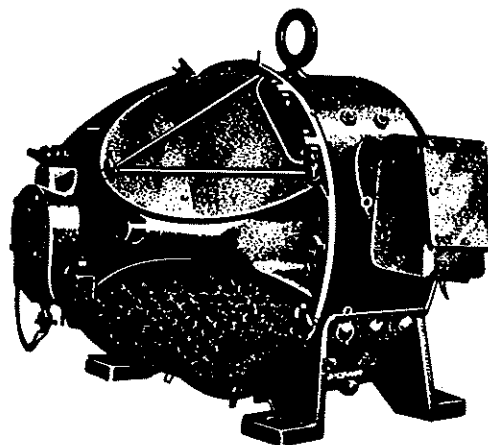
The open-type motor shown in figure 15-2 (A) has end bells which offer little or no restriction to ventilation. The drip-proof motor shown in figure 15-2 (B) is protected from falling moisture and dirt from any direction up to a 45° angle

with respect to the vertical. A motor of this type has all ventilation openings protected with wire screens or perforated covers, as shown in the figure. An enclosed motor like the one in figure 15-2 (C) is totally enclosed except for openings provided for the admission and discharge of air. These openings are connected to inlet and outlet ducts or pipes.

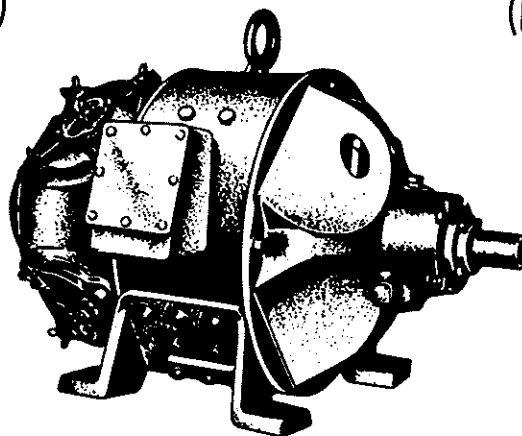
Other motor types include a spray-tight motor so constructed that a stream of water from a hose may be played upon it from any direction without leakage into the motor.



OPEN-TYPE MOTOR
(A)



DRIP-PROOF MOTOR
(B)



ENCLOSED MOTOR
(C)

Figure 15-2.—Types of shipboard d-c motors classified according to enclosure.

A submersible motor is one that will operate while submerged in liquid.

With reference to cooling, the following types of motors are found aboard ship:

1. **NATURAL VENTILATED MOTORS**, cooled by the natural circulation of the air caused by the rotation of the armature.

2. **SELF-VENTILATED MOTORS**, cooled by a fan attached to the armature of the motor.

3. **SEPARATELY VENTILATED MOTORS**, cooled by an independent fan or blower apart from the motor.

With reference to speed, motors are classified as:

1. **CONSTANT-SPEED MOTORS** in which the speed varies only slightly between no load and full load. A shunt motor is a constant-speed motor.

2. **MULTISPEED MOTORS** which can be operated at any one of several definite speeds, each speed being nearly constant with load change. Such motors cannot be operated at intermediate speeds. A motor with two windings on the armature is an example of a multi-speed motor.

3. **ADJUSTABLE-SPEED MOTORS** whose speed can be varied gradually over a wide range, but when once adjusted remains at nearly constant speed with load change.

4. **VARYING SPEED MOTORS** in which the speed varies with the load. Ordinarily the speed decreases as the load increases. The series motor is an example of this type of motor.

5. **ADJUSTABLE VARYING SPEED MOTORS** in which the speed may be adjusted over a wide range for any given load; but if the speed is adjusted at a given load, the speed will vary with any change in load.

Motors are also classified according to the type of duty they are to perform. For example, a **CONTINUOUS-DUTY MOTOR** is capable of operating continuously at its rated output without exceeding specified temperature limits. An **INTERMITTENT-DUTY MOTOR** is capable of being operated at its rated output for a limited period without exceeding its specified temperature limit.

Most d-c motors on vessels are designed to operate on constant-potential 2-wire circuits of either 115 volts or 230 volts. These circuits may be combined in a 3-wire d-c supply with 230 volts between each outside wire, and 115 volts between each outside wire and middle or neutral wire.

D-c motors find extensive use on aircraft. The motors used on aircraft operate on the same principles as the larger motors aboard ship. However, the airborne motors differ considerably in size, rating, and appearance, as illustrated in figure 15-3. Also, they are designed to operate from a 24-28 volt d-c source.

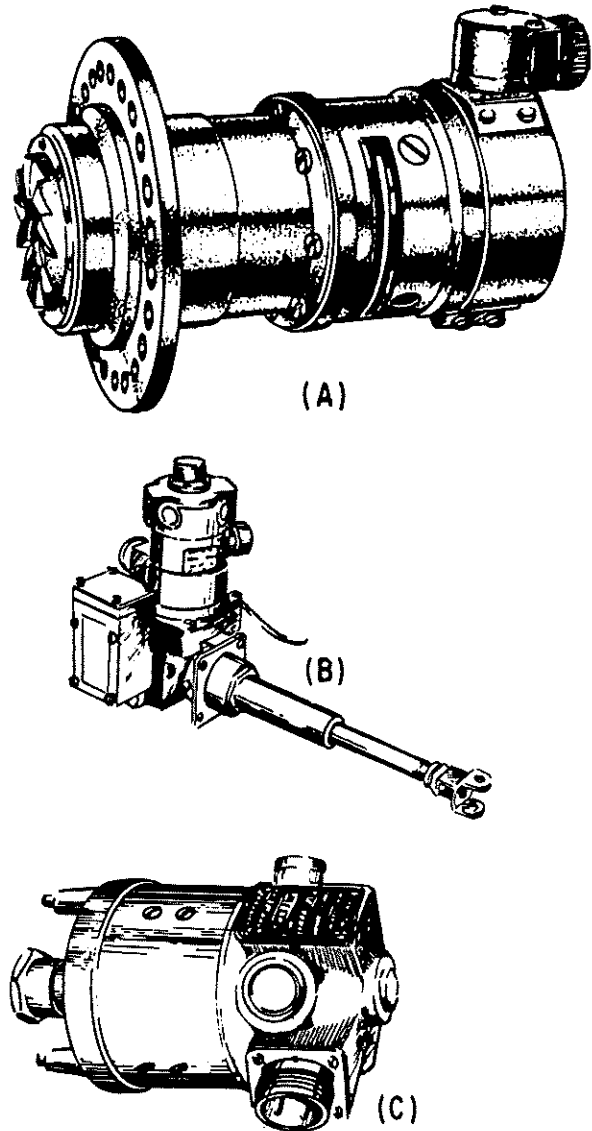


Figure 15-3.—Aircraft d-c motors.

Part (A) is an aircraft engine starter motor. Starters are series motors, selected to supply the typically high torque required for engine

starting. They are usually the largest motors on the aircraft, with power outputs up to twenty h.p., but are designed only for intermittent use. Part (B) is one of many types of d-c motors used to actuate mechanical loads, in this case cowl flaps. Such loads may include wing flaps, cowl flaps, landing gear, cockpit canopies, and bomb bay doors. Actuator motors are also of the series type, since they must start under full mechanical load. Many airborne actuator motors

are of the series split-field type, and are reversible. Most are also designed only for intermittent use. Part (C) is a continuous-duty d-c motor, in this case one that is used to drive windshield wipers. Continuous-duty motors on aircraft are usually of the compound type. The most recent trend in aircraft design is to use d-c motors for intermittent duty, and a-c motors for continuous duty.

Principles of D-C Motors

FORCE ACTING ON A CONDUCTOR

The operation of a d-c motor depends on the principle that a current-carrying conductor placed in, and at right angles to, a magnetic field tends to move at right angles to the direction of the field, as shown in figure 15-4. This action was previously described under the operating principle of the D'Arsonval meter movement.

The magnetic field between a north and a south pole of a magnet is shown in figure 15-4 (A). The lines of force, comprising the field extend from the north pole to the south pole. A cross section of a current-carrying conductor is shown in figure 15-4 (B). The plus sign in the wire indicates that the electron flow is away from the observer. The direction of the flux loops around the wire is counterclockwise, as shown. This follows from the left-hand flux rule which states that if the conductor is grasped in the left hand with the thumb extended in the direction of the current flow, the fingers will curve around the conductor in the direction of the magnetic flux.

If the conductor (carrying the electron flow away from the observer) is placed between the poles of the magnet, as in figure 15-4 (C), both fields will be distorted. Above the wire the field is weakened, and the conductor tends to move upward. The force exerted upward depends on the strength of the field between the poles and on the strength of the current flowing through the wire.

If the current through the conductor is reversed, as in figure 15-4 (D), the direction of the flux around the wire is reversed. The field below the conductor is now weakened, and the conductor tends to move downward.

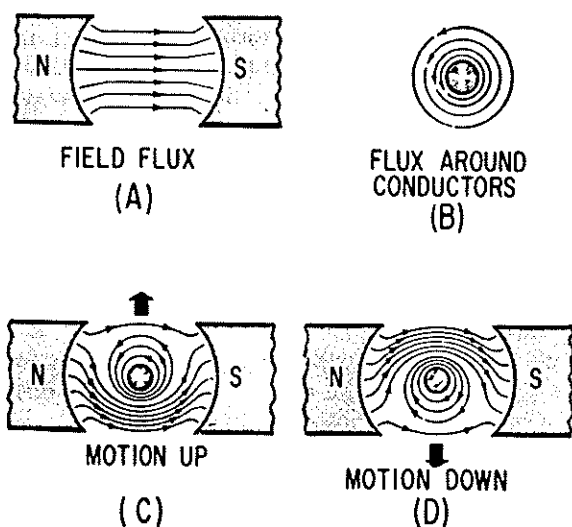


Figure 15-4.—Force acting on a current-carrying conductor in a magnetic field.

A convenient method of determining the direction of motion of a current-carrying conductor in a magnetic field is by the use of the right-hand motor rule. Practical d-c motors depend for their operation on the interaction between the field flux and a large number of current-carrying conductors. As in d-c generators, the conductors are wound in slots in the armature; and the armature is mounted in bearings and is free to rotate in the magnetic field. An armature with two slots and two conductors (that is, a single conductor wound in the two slots) is shown in figure 15-5.

Figure 15-5 (A) shows the uniform distribution of the main field flux when the field magnets are energized, and no current flows through the armature. The flux is concentrated in the air gap between the field and armature

because of the relatively high permeability of the soft-iron armature core and the low reluctance of the magnetic circuit.

Figure 15-5 (B) shows the magnetic fields surrounding the two active conductors when current flows through the armature coil in the direction indicated, and the field coils are not energized. The direction of the magnetic fields surrounding the two conductors is determined by means of the left-hand flux rule.

Figure 15-5 (C) shows the resultant magnetic field produced by the interaction of the main field magnetomotive force and the armature magnetomotive force. Note that the flux is strengthened below the conductor at the north pole and above the conductor at the south pole because the lines are in the same directions at these points. Conversely, the flux is weakened above the conductor at the north pole and below the conductor at the south pole because the lines are opposite in direction and tend to cancel each other. The lines of force act like stretched rubber bands that tend to contract, with the result that the armature rotates in a clockwise direction. If either the direction of current through the armature coil or the polarity of the field is reversed (but not both), the direction of the force on the armature conductors reverses. If both the field polarity and the armature current are reversed, rotation continues in the same direction.

A practical d-c motor has many coils in the armature winding. The armature has many slots into which are inserted many turns of wire. This increases the number of armature conductors and thus produces a greater, more constant torque. Power output is also increased by increasing the number of poles in the field.

As in the case of the d-c generator, the d-c motor is equipped with a commutator and brushes.

The force, F , acting on a current-carrying conductor in a magnetic field is directly proportional to the field strength, the active length of the conductor (that part of the conductor contained in the armature slot and lying under a pole face), and the current flowing through it. The force, the conductor, and the field are assumed to be mutually perpendicular. This relationship is expressed algebraically as

$$F = \frac{8.85 \times B L I}{10^8}$$

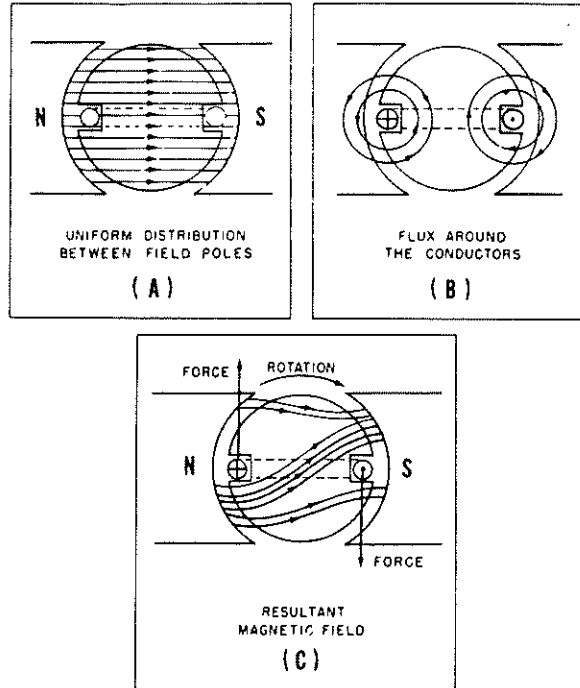


Figure 15-5.—Two-conductor armature.

where F is the force in pounds, B the flux density in lines per square inch, L the active length of the conductor in inches, I the current in amperes flowing through the conductor, and 8.85 is a constant that must be used when the above units are employed.

In a given motor, the length of the conductor is a fixed quantity: therefore, the only variables are the current and the flux. If the field flux is constant, the force acting on the conductor varies directly as the armature current. In other words, F is proportional to I . The following example will illustrate how the force acting on a conductor is calculated.

If a conductor having an active length of 10 inches and a current of 30 amperes is placed in a uniform field of 37,700 lines per square inch, what force will be exerted on the conductor?

$$F = \frac{8.85 B L I}{10^8} = \frac{8.85 \times 37,700 \times 10 \times 30}{10^8} = 1 \text{ pound.}$$

If the conductor is wound around an armature (fig. 15-5 (C)) and the armature current flows in the directions shown, there will be an upward force of one pound on the left of the armature and a downward force of one pound on the

DIRECT-CURRENT MOTORS

right of the armature. The net force acting to turn the armature is the sum of these two forces, or two pounds.

TORQUE

The TORQUE (or twist) on the armature is the product of the force acting at the surface of the armature times the perpendicular distance to the center of rotation of the armature. Assume the radius of the armature being considered is 1.5 feet, the torque exerted by each conductor is $1 \times 1.5 = 1.5$ pound-feet; and the total torque exerted by both conductors is $1.5 + 1.5 = 3$ pound-feet.

The armature conductors for a motor are assembled in coils and connected to the commutator riser exactly as in a generator. In the 2-pole motor (fig. 15-6 (A)), the current divides equally in the two paths through the armature. Current flows in one direction in the conductors under the north pole and in the opposite direction in the conductors under the south pole. To develop a continuous motor torque the current in a coil must reverse when the coil passes the dead center position (top and bottom). The function of the commutator is to reverse the current at the proper time to maintain the current flow in the same direction in all conductors under a given pole. The total torque is the sum of the individual torques contributed by all the armature conductors. If there are 200 active conductors each developing a force of 1 pound the total torque will be $200 \times 1 \times$ the average moment arm.

The AVERAGE MOMENT ARM is the average of all the perpendicular distances from the armature conductors to the center of rotation. If the field is assumed to consist of uniformly spaced horizontal lines of flux, the average moment arm will be 0.637 of the maximum moment arm, or radius, of the armature.

If the radius of the armature is 1.57 feet, the average moment arm is $0.637 \times 1.57 = 1$ foot. The total torque exerted by 200 armature conductors developing a force of 1 pound each is $200 \times 1 \times 1 = 200$ pound-feet.

In a 4-pole parallel-wound armature, the current divides into four paths as shown in figure 15-6 (B). The current flows in opposite directions under alternate poles, as in the 2-pole armature, and develops a unidirectional force on all of the armature conductors. The total torque produced by the armature current is equal to the

sum of the individual torques developed by each conductor. This torque, T , is proportional to the product of armature current and field strength.

$$T = K_f \Phi I_a, \quad (16-1)$$

where K_f is a constant that includes the number of armature conductors, number of paths, and other factors which are constant for a particular machine; Φ the flux per pole and I_a the total armature current. When the speed of a motor is constant, the generated torque due to the armature current is just equal to the retarding torque caused by the combined effect of the friction losses in the motor and the mechanical load. The torque developed by the motor armature is a steady one and does not pulsate as in the case of reciprocating steam engines or internal combustion engines.

HORSEPOWER OF A MOTOR

If the number of revolutions that the armature of a motor makes per minute (or per second), the effective armature radius at which the force acts, and the total force acting at and tangent to this effective radius are known, the horsepower may be determined. Briefly, the horsepower may be determined in the following manner.

Work is accomplished when force acts through distance. For example, when a force of one pound acts through a distance of one foot, one foot-pound of work is accomplished. If 33,000 foot-pounds of work is done in one minute, one horsepower of work is accomplished.

Assume that an armature makes 100 revolutions per minute and that the effective radius is 1.59 feet. The circumference (the distance through which the force moves in one revolution of the armature) is

$$\begin{aligned} \text{circumference} &= 2\pi r \\ &= 2 \times 3.14 \times 1.59 = 10 \text{ feet.} \end{aligned}$$

Assuming that a total effective force of 200 pounds acts on the armature tangent to the 10-foot circumference, the work done in one revolution is

$$\text{work} = \text{force} \times \text{distance} = 200 \times 10 = 2,000 \text{ foot-pounds.}$$

The work done in 100 revolutions (one minute) is

$$2,000 \times 100 = 200,000 \text{ foot-pounds.}$$

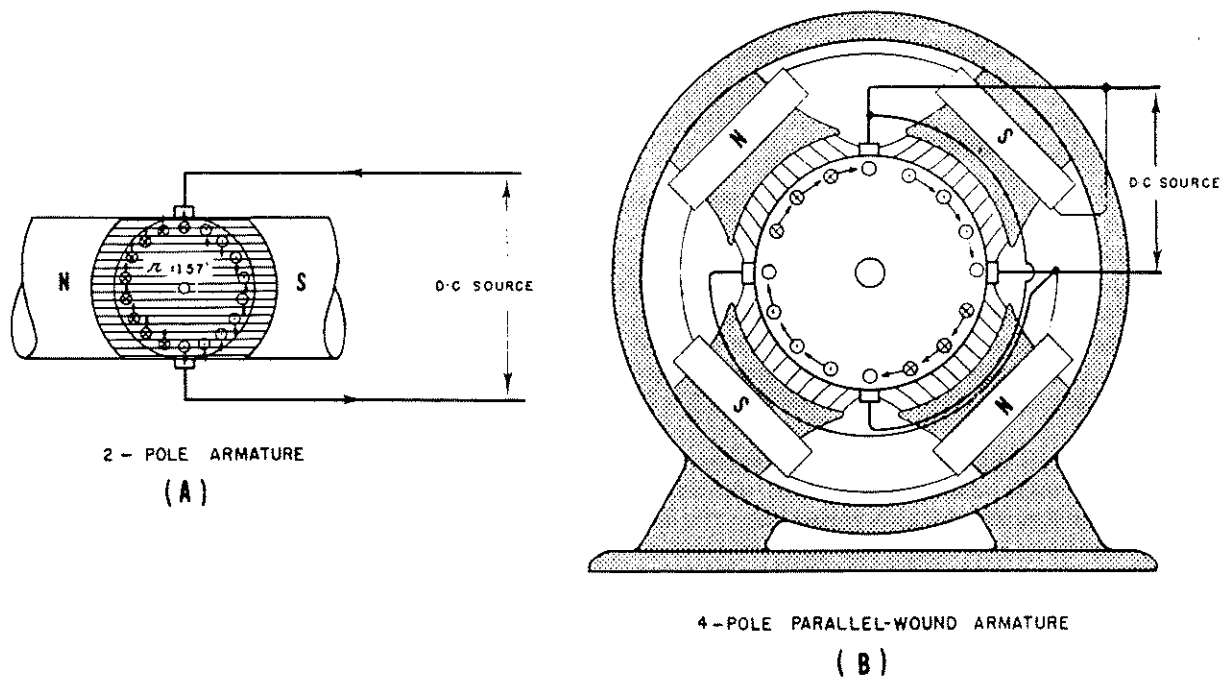


Figure 15-6.—Torque developed in a motor armature.

The horsepower is therefore,

$$\text{h.p.} = \frac{\text{foot-pounds per minute}}{33,000} = \frac{200,000}{33,000} = 6.06 \text{ horsepower.}$$

The horsepower developed by a motor armature may be derived from the general expression.

$$\text{h.p.} = \frac{FV}{33,000}, \quad (15-2)$$

where F is the total force in pounds tangent to the effective circumference of the armature, and V the velocity of a point on this circumference in feet per minute. Velocity is determined as

$$V = 2\pi rN, \quad (15-3)$$

where r is the effective radius of the armature in feet, and N is the armature speed in revolutions per minute. The effective circumference is equal to $2\pi r$.

Substituting equation (15-3) in equation (15-2),

$$\text{h.p.} = \frac{2\pi rNF}{33,000} \quad (15-4)$$

The torque in pound-feet produced by the motor armature is

$$T = rF. \quad (15-5)$$

Substituting equation (15-5) in equation (15-4) and dividing numerator and denominator by 2π ,

$$\text{h.p.} = \frac{NT}{5,252}. \quad (15-6)$$

Substituting the values $N = 100$ r.p.m. and $T = 1.59 \times 200 = 318$ pound-feet of the preceding example in equation (15-6), the result is

$$\text{h.p.} = \frac{100 \times 318}{5,252} = 6.06.$$

Thus, the horsepower developed by a motor depends on its speed and torque. Large, slow-speed motors develop a large torque; whereas other much smaller motors of the same horsepower rating operate at reduced torque and increased speed.

COUNTER E.M.F.

The MOTOR ACTION of a generator was treated in Chapter 14 the GENERATOR ACTION of a motor is now considered. By applying the right-hand motor rule to an armature conductor carrying current in the direction indicated in figure 15-7, it will be found that the conductor is forced upward. As the conductor

is moved up through the field, it cuts lines of flux and has a voltage induced in it. Applying the left-hand generator rule, it is found that this generated voltage is in opposition to the impressed e.m.f. This counter voltage is induced in the windings of any rotating motor armature and always opposes the impressed voltage. It is called COUNTER ELECTROMOTIVE FORCE and is directly proportional to the speed of the armature and the field strength. That is, the counter e.m.f. is increased or decreased if the speed is increased or decreased respectively; the same is true if the field strength is increased or decreased.

The EFFECTIVE VOLTAGE (IR drop) in the armature is equal to the impressed voltage minus the counter e.m.f. The armature IR drop varies directly with the current flowing in the armature and the resistance of the armature.

To produce an armature current, I_a , in an armature of resistance, R_a , requires an effective voltage of $I_a R_a$.

The current flowing through the armature can be found by the equation

$$I_a = \frac{E_a - E_c}{R_a},$$

where I_a is the current flowing through the armature, E_a the impressed (or applied) voltage across the armature, E_c the counter e.m.f., and R_a the armature resistance. This equation can be transposed and written as

$$E_c = E_a - I_a R_a. \quad (15-7)$$

In the case of the generator, the generated e.m.f. is equal to the terminal voltage plus the armature resistance drop; and in the case of the motor the generated or counter e.m.f. is equal to the terminal voltage minus the voltage drop in the armature resistance.

Expressing E_a in terms of E_c and $I_a R_a$,

$$E_a = E_c + I_a R_a.$$

This formula is valid for any d-c motor regardless of speed or load.

The counter e.m.f., E_c , that is induced in a motor armature may be determined by an equation similar to that used to determine the generator voltage in a generator. This equation is

$$E_c = \frac{\Phi Z N P}{10^8 p}, \quad (15-8)$$

where Φ is the number of lines of flux per pole, Z the number of face conductors, N the armature speed in revolutions per second, P the number of field poles, and p the number of parallel paths through the armature circuit.

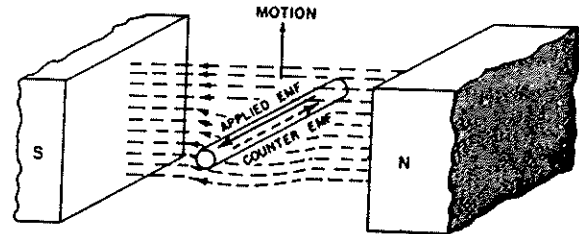


Figure 15-7.—Generator action in a motor.

ARMATURE REACTION

The armature current in a generator flows in the same direction as the generated e.m.f., but the armature current in a motor is forced to flow in the opposite direction to that of the counter e.m.f. Assume that the field of the motor (fig. 15-8 (A)) is of the same polarity as the field of the generator (fig. 14-12 (A)). For the same direction of armature rotation, the armature flux of the motor (fig. 15-8 (B)) is in the opposite direction to that of the generator (fig. 14-12 (B)). In a motor the main field flux is always distorted in the opposite direction to rotation (fig. 15-8 (C)), whereas in a generator the main field flux is distorted (fig. 14-12 (C)) in the same direction as that of rotation. Note that the resultant field in the motor (fig. 15-8 (C)) is strengthened at the leading pole tips and weakened at the trailing pole tips. This action causes the electrical neutral plane to be shifted back to $A'B'$. Thus, to obtain good commutation in a motor without interpoles, it is necessary to shift the brushes from the mechanical neutral, AB , in a direction opposite to that of the armature rotation.

The armature reaction is overcome in a motor by the same methods as for the generator — that is, by the use of laminated pole tips with slotted pole pieces, and compensating windings. In each case the effect produced is the same as that produced in the generator, but it is in the opposite direction.

COMMUTATION

The brush axis, $A'B'$ (fig. 15-8 (C)), could be made to coincide exactly with the neutral plane of the combined field. This would eliminate sparking at the brushes if it were not for the self-induced e.m.f. in the commutated coils. Because of the necessity for neutralizing this e.m.f. to eliminate sparking, the brushes must

be set slightly behind the neutral plane in a motor. Thus, in both the generator and the motor, the brushes must be moved from the mechanical neutral slightly beyond the electrical neutral plane to neutralize the effect of self-inductance.

The current flowing in the armature coils of a motor (fig. 15-9) must be periodically reversed when the coils are being short-circuited by the

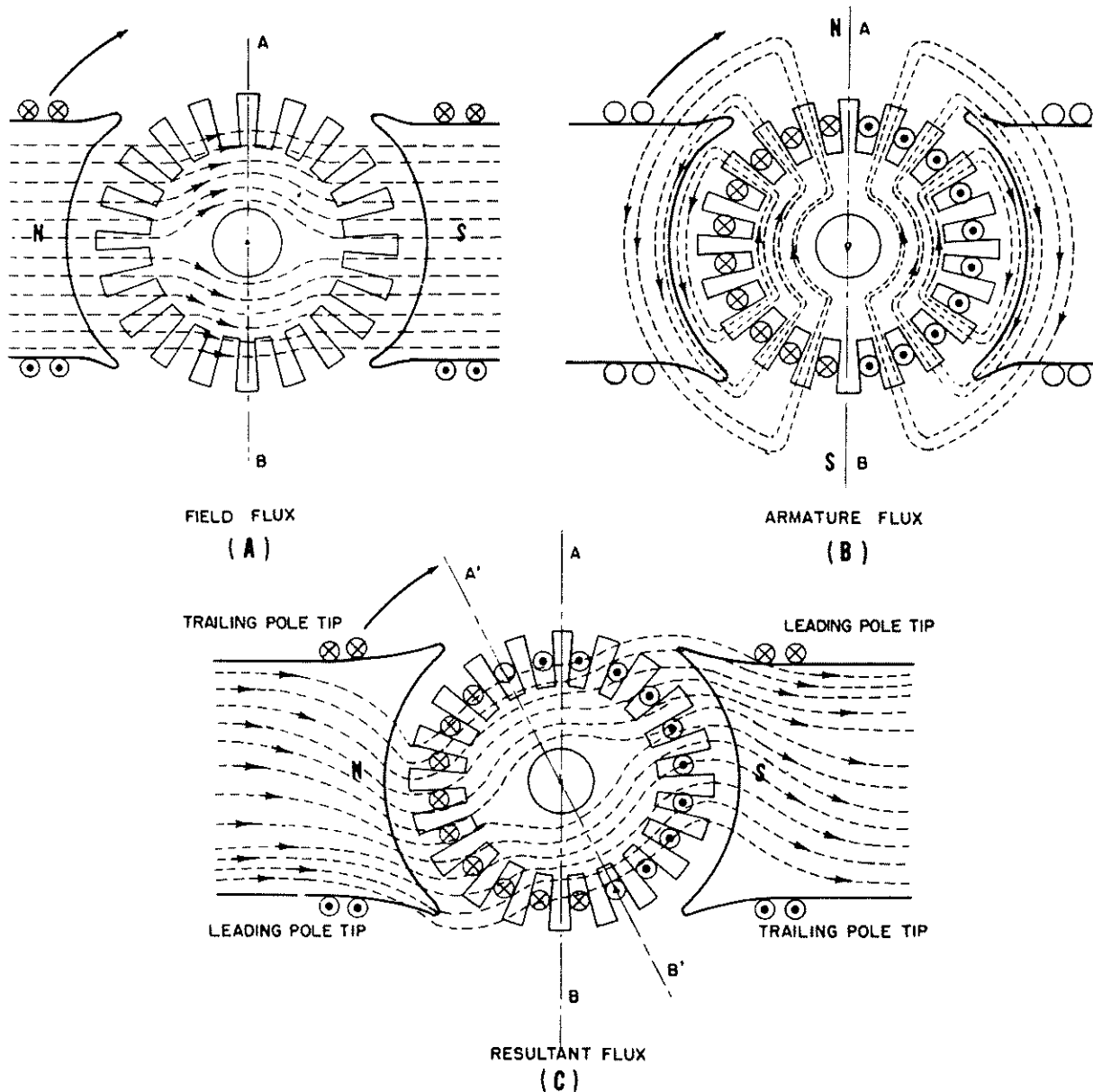


Figure 15-8.—Armature reaction in a motor.

brushes in order to maintain a unidirectional torque as the coils move under alternate poles. When coil *A* is short circuited by a brush, its current immediately starts to decrease to zero; from zero, the current then builds up to a maximum in the reversed direction by the time the coil moves from position ① to position ②, where the brush no longer short circuits it. As a result of the changing current, a self-induced voltage is set up in the shorted coil, which tends to keep the current from changing. To obtain sparkless commutation it is necessary to overcome this self-induced voltage.

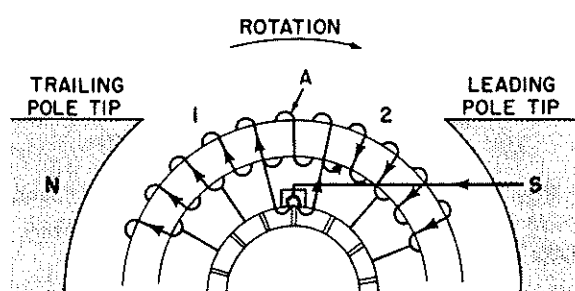


Figure 15-9.—Commutation in a motor.

In any motor the current flows as a result of the applied voltage, and the counter e.m.f. opposes the flow of current. As the current in the commutated coil decreases to zero, the e.m.f. of self-induction tends to keep the current flowing in the same direction, as indicated by the arrow in position ①. Therefore, it aids the applied voltage during this portion of the cycle. As the coil moves into position ② the current increases in the opposite direction, and the self-induced voltage again opposes this current increase. To overcome the self-induced voltage another voltage is introduced into the coil, which opposes the self-induced voltage. The counter e.m.f. is in the proper direction to accomplish this, but the coil being commutated is in the neutral plane and consequently has no counter e.m.f. generated in it.

When the brushes are shifted against the direction of rotation, the coils that are being shorted by the brushes still cut lines of flux from the previous north pole and have a small amount of counter e.m.f. generated in them. Because this counter e.m.f. opposes the applied voltage it also opposes the self-induced voltage, thus resulting in rapid reversal of coil current and in sparkless commutation.

When the load on the motor increases, armature reaction increases and the electrical neutral plane is shifted further in the direction opposite to that of the armature rotation. To maintain sparkless commutation, the plane of the brushes will have to be shifted slightly beyond the electrical neutral plane. When the load is reduced, the brushes are shifted in the opposite direction. Thus, for sparkless commutation, it is necessary to manually shift the brushes when the load varies.

COMMUTATING POLES

Commutating poles are as important in motors as in generators. Nearly all motors of more than one horsepower depend on COMMUTATING POLES, sometimes called INTERPOLES, rather than on the shifting of the brushes to obtain sparkless commutation. Essentially the only difference between the interpole generator and the interpole motor is that in the generator the interpole has the same polarity as the main pole AHEAD of it in the direction of rotation, but in the motor the interpole has the same polarity as the main pole BACK of it.

Without interpoles the e.m.f. of self-induction is overcome by commutating the coil while it is cutting the flux of the main pole it is just leaving. Therefore, if the interpole is to overcome the e.m.f. of self-induction, it must have the same polarity as the main pole it is leaving. This is a north pole in the example of figure 15-9.

The interpole series field coil in a motor is connected to carry the armature current, as in the generator. As the load varies, the interpole flux varies, and commutation is automatic with load change. It is not necessary to shift the brushes when there is an increase or decrease in load. The brushes are located on the no-load neutral and remain in that position for all conditions of load.

The motor may be reversed by reversing the direction of the current in the armature. When the armature current is reversed, the current through the interpole is also reversed, and therefore the interpole still has the proper polarity to provide automatic commutation.

The direction of the counter e.m.f. in the interpole motor with clockwise rotation (fig. 15-10) illustrates that coils under the interpoles do not contribute to the armature counter voltage, but that only those coils under the main

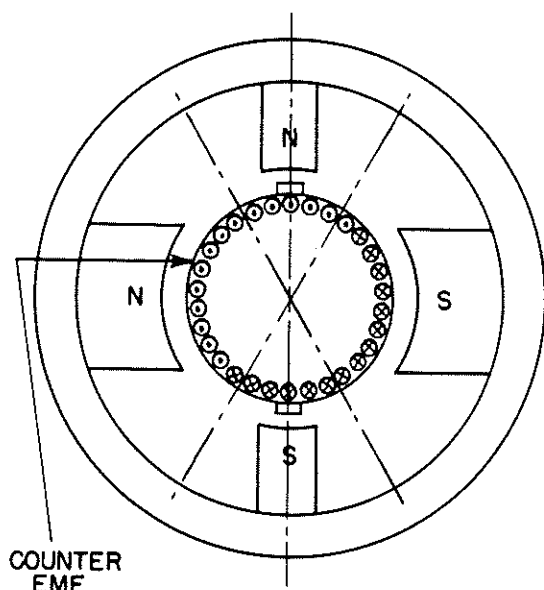


Figure 15-10.—Effect of interpoles on armature counter e.m.f.

poles contribute to it. The total counter voltage generated in the conductors on each half of the armature is equal to the algebraic sum of the voltages generated in each conductor between the upper and lower brush. Because those under the upper north interpole generate an equal and opposite voltage to those under the lower south interpole, the remaining conductors under the main field poles generate the armature counter e.m.f. that controls the armature load current and the speed-torque characteristics of the motor. It is important that the brushes be set

in the correct neutral plane, otherwise the commutation will be impaired and the motor characteristics will be altered.

SPEED REGULATION

SPEED REGULATION is the ability of a motor to maintain its speed when a load is applied. It is an inherent characteristic of a motor and remains the same as long as the applied voltage does not vary — that is, unless a physical, or mechanical, change is made in the machine. The speed regulation of a motor is a comparison of its no-load speed to its full-load speed and is expressed as a percentage of full-load speed. Thus,

percent speed regulation =

$$\frac{\text{no-load speed} - \text{full-load speed}}{\text{full-load speed}} \times 100.$$

For example, if the no-load speed of a shunt motor is 1,600 r.p.m. and the full-load speed is 1,500 r.p.m. the speed regulation is

$$\frac{1,600 - 1,500}{1,500} \times 100 = 6.6 \text{ percent.}$$

The LOWER the speed-regulation percentage figure of a motor, the more constant the speed will be under varying load conditions and the BETTER will be the speed regulation. The HIGHER the speed-regulation percentage figure, the POORER is the speed regulation.

SPEED CONTROL refers to the external means of varying the speed of a motor under any load.

Shunt Motors

SPEED REGULATION OF A SHUNT MOTORS

The field circuit of a shunt motor is connected across the line and is thus in parallel with the armature the same as it is in the shunt generator (fig. 14-16 (B)). If the supply voltage is constant, the current through the field coils, and consequently the field flux, will be constant.

When there is no load on the shunt motor, the only torque necessary is that required to overcome bearing friction and windage. The rotation of the armature coils through the field flux establishes a counter e.m.f. that limits the armature current to the relatively small value required to establish the necessary torque to run the motor on no load.

When an external load is applied to the shunt motor it tends to slow down slightly. The slight decrease in speed causes a corresponding decrease in counter e.m.f. If the armature resistance is low, the resulting increase in armature current and torque will be relatively large. Therefore, the torque is increased until it matches the resisting torque of the load. The speed of the motor will then remain constant at the new value as long as the load is constant.

Conversely, if the load on the shunt motor is reduced, the motor tends to speed up slightly. The increased speed causes a corresponding increase in counter e.m.f. and a relatively large decrease in armature current and torque.

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Thus, it may be seen that the amount of current flowing through the armature of a shunt motor depends on the load on the motor. The larger the load, the larger the current; and conversely, the smaller the load, the smaller the current. The change in speed causes a change in counter e.m.f. and armature current in each case.

Figure 15-11 indicates graphically what happens when the load is applied or removed from a shunt motor. In this figure it is assumed that the field strength remains constant.

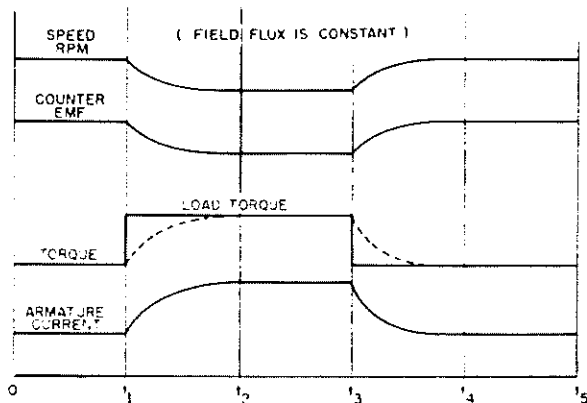


Figure 15-11.—Shunt motor load-speed-torque-e.m.f. relationships with respect to time.

During the interval between 0 and t_1 the motor operates under conditions of equilibrium — that is, the speed, counter e.m.f., torque, and armature current have steady values. At t_1 a load is applied to the motor. Instantly, the load-torque curve rises, but the inertia of the armature prevents the generated torque from rising instantly with it. Because the load torque exceeds

the generated torque in the motor armature, the motor speed is reduced until a balance is again obtained. When the generated torque is again equal to the load torque deceleration ceases and the motor operates at a constant reduced speed.

At time t_2 this state of equilibrium, corresponding to the new load, is reached. At time t_3 the load is suddenly removed. The load torque drops instantly, but the armature inertia prevents the generated torque from falling instantly with it. Likewise, the armature inertia prevents the armature speed from increasing suddenly. Because the generated torque exceeds the load torque, the motor accelerates. As the speed increases, the counter e.m.f. increases proportionately. This opposes the applied e.m.f., and the armature current is reduced until the generated torque and load torque are again in a state of equilibrium. The speed then levels off to a constant value.

The operational features of a shunt motor are indicated in table 15-1. The variation of line current, armature current, counter e.m.f., speed, torque, and efficiency, with varying load conditions are indicated. The values are based on a 1-horsepower 100-volt shunt motor having a field current of 1 ampere and an armature resistance of 1 ohm.

When the armature current is 1 ampere the armature IR drop is 1 volt, and the counter e.m.f. is the difference between the applied voltage and the IR drop, or $100 - 1 = 99$ volts. The speed at this load is assumed to be 990 r.p.m. At this load the motor torque is assumed to be 0.7 pound-foot. The output power, P_o , in watts is

$$P_o = \frac{NT}{5,252} \times 746 = 0.142 NT = 0.142 \times 990 \times 0.7 = 98.4 \text{ watts.}$$

Table 15-1.—Operational features of a shunt motor.

I Line (amperes)	I Arma- ture (amperes)	Counter e.m.f. (volts)	Speed (r.p.m.)	Torque (lb.-ft)	Output 0.142NT (watts)	Input (watts)	Effi- ciency (percent)	Load
¹ 2	¹ 1	¹ 99	¹ 990	¹ 0.7	98.4	200	49.2	Light.
4	3	97	970	2.1	289	400	72.2	Do.
6	5	95	950	3.5	472	600	78.5	Do.
8	7	93	930	4.9	646	800	80.8	Do.
10	9	91	910	6.3	815	1,000	81.5	Normal.
21	20	80	800	14	1,590	2,100	76	Over.

¹ Assumed.

The constant 746 is used to convert horsepower output into an equivalent number of watts output (1 horsepower = 746 watts).

The total input current to the motor is equal to the sum of the field current and the armature current, or $1 + 1 = 2$ amperes. The input power is the product of the applied voltage and the total input current, or $100 \times 2 = 200$ watts. The efficiency is

$$\frac{\text{output}}{\text{input}} \times 100 = \frac{98.4}{200} = 49.2 \text{ percent at this load.}$$

The torque calculations for other values of load are based on the proportionality between armature current and torque. For example, if the torque is 0.7 pound-foot when the armature current is 1 ampere, the torque for an armature current of 2 amperes will be $2 \times 0.7 = 1.4$ pound-feet.

The speed calculations are based on the proportionality between speed and counter voltage. For example, when the armature current is 2 amperes the armature IR drop is $2 \times 1 = 2$ volts, and the counter e.m.f. is $100 - 2 = 98$ volts. If the speed is 990 r.p.m. when the counter e.m.f. is 99 volts, the speed at 98 volts counter e.m.f. will be 980 r.p.m.

The characteristic curves of a 5-horsepower 230-volt shunt motor are shown in figure 15-12. These curves include speed, torque, efficiency, and input current. The speed curve is almost a horizontal line, and the regulation is good. The torque varies directly with the output load and armature current because the field is approximately constant over the load range.

The speed regulation of a shunt motor is generally better than the voltage regulation of the same machine when operating as a shunt generator. This action is due to the fact that armature reaction in a generator weakens the field and lowers the terminal voltage, whereas armature reaction in a motor weakens the field and tends to increase the motor speed. Armature resistance is low, and a decrease in field strength and counter e.m.f. (for example, of 5 percent) might result in an increase in armature current and accelerating force on the armature conductors of 50 percent with resulting

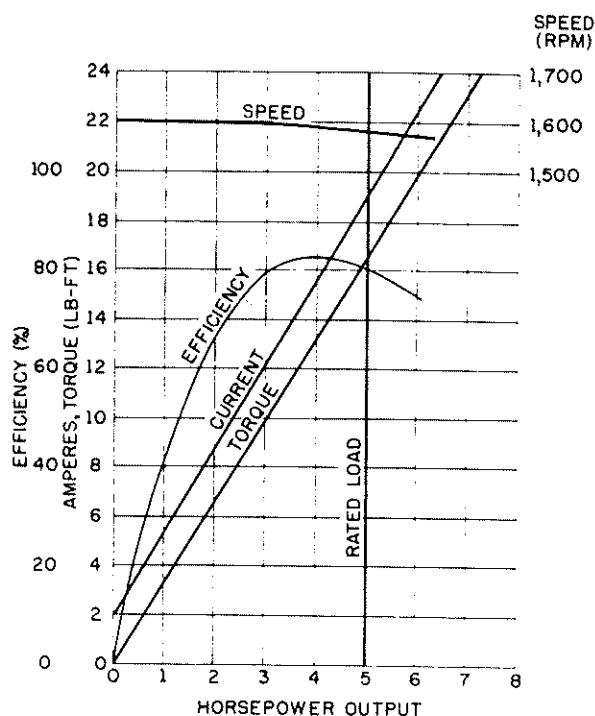


Figure 15-12.—Characteristic curves of a shunt motor.

increase in armature speed. In general, however, armature reaction in a motor weakens the field only slightly and does not cause the speed to increase with load, but to decrease less than it would if the armature reaction were not present.

USES OF SHUNT MOTORS

From the preceding considerations it is evident that a shunt motor is essentially a constant-speed machine. Although the speed may be varied by varying the current through the field winding (for example, by means of a field rheostat), the speed remains nearly constant for a given field current.

The constant-speed characteristic makes the use of shunt motors desirable for driving machine tools or any other device that requires a constant-speed driving source.

Where there is a wide variation in load, or where the motor must start under a heavy load, series motors have desirable features not found in shunt motors.

Series Motors

SPEED REGULATION OF SERIES MOTORS

The field coils of a series motor are connected in series with the armature like those of

the series generator in figure 14-16 (B). With relatively low flux density in the field iron, the series field strength is proportional to armature

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current I_a . The torque developed by the motor armature is proportional to $I_a \Phi$; and because Φ is also proportional to I_a , the torque is proportional to I_a^2 .

If the supply voltage is constant, the armature current and the field flux will be constant only if the load is constant. If there were no load (this is never done) on the motor, the armature would speed up to such an extent that the windings might be thrown from the slots and the commutator destroyed by the excessive centrifugal forces. If the load is removed from the motor, the armature will speed up and a higher counter e.m.f. will be induced in the armature. This reduces the current through the armature and the field. The weakened field causes the armature to turn faster. The counter e.m.f. is thus increased, and the speed is further increased until the machine is destroyed. For this reason, series motors are never belt-connected to their loads. The belt might come off and the motor would then overspeed and destroy itself. Series motors are always connected to their loads directly, or through gears.

USES OF SERIES MOTORS

As indicated in figure 15-13, the torque increases with load. When the load on a series motor is increased, the speed and the counter e.m.f. decrease and the armature current and field strength increase. There is therefore an increase in torque with decrease in speed with the result that the increased load on the motor is limited by the decrease in speed.

When a heavy load is suddenly thrown on a shunt motor, it attempts to take on the load at only slightly reduced speed and counter emf. The flux remains essentially constant and therefore the increased torque is proportional to the increase in armature current. With heavy overload the armature current becomes excessive and the temperature increases to a very high value. The shunt motor cannot slow down appreciably on heavy load, as can the series motor; hence the shunt motor is more susceptible to overload.

For example, assume that a d-c motor is used to move an electric truck up an incline. If it is a shunt motor it will attempt to maintain almost the same speed up the incline as on the level and consequently excessive current may be drawn through the armature, since the field flux remains almost constant. If it is a series

motor, the speed must decrease more than the flux increases in order to have a reduction in counter e.m.f. and an increase in armature current ($E_c - \frac{\Phi ZNP}{10^8 p}$). The decrease in speed protects the series motor from excessive overload, and the armature current is limited by the

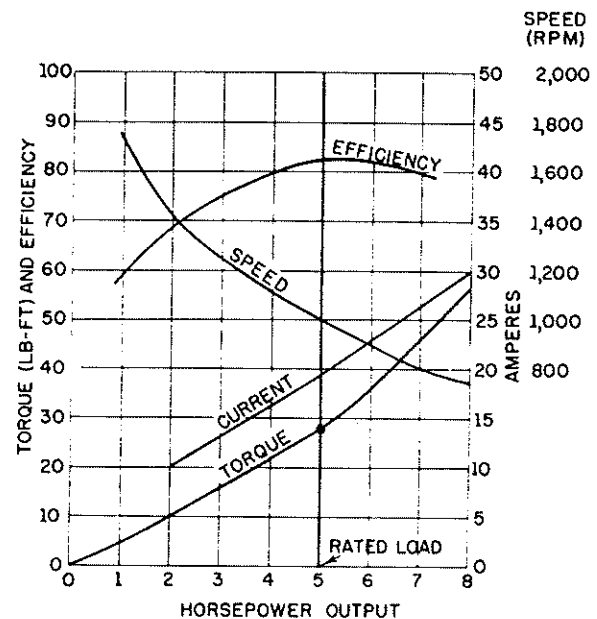


Figure 15-13.—Characteristic curves of a series motor.

counter voltage and the combined resistance of the armature and series field.

The series motor is therefore used where there is a wide variation in both torque and speed such as in traction equipment, blower equipment, hoists, cranes, and so forth.

Compound Motors

Compound motors, like compound generators, have both a shunt and a series field. In most cases the series winding is connected so that its field aids that of the shunt winding, as shown in figure 15-14 (A). Motors of this type are called **CUMULATIVE COMPOUND** motors. If the series winding is connected so that its field opposes that of the shunt winding, as shown in figure 15-14 (B), the motor is called a **DIFFERENTIAL COMPOUND** motor. Under full load, the ampere-turns of the shunt coil are greater than the ampere-turns of the series coil.

In the **CUMULATIVE COMPOUND** motor the speed decreases (when a load is added) more rapidly than it does in a **SHUNT** motor, but less rapidly than in a **SERIES** motor. Series field strength increases as in a series motor. Transposing equation (15-10) for armature current,

$$I_a = \frac{E - E_c}{R_a + R_s}$$

To increase I_a , E_c must decrease. As in the series motor, the decrease in speed is necessary

to allow the counter e.m.f. to decrease at the same time the field increases. Because the torque varies directly as the product of the armature current and the field flux (equation 15-1), it is evident that the cumulative compound motor has greater starting torque than does the shunt motor for equal values of armature current and shunt field strength. The performance of this type of motor approaches that of a shunt motor as the ratio of the ampere-turns of the shunt winding to the ampere-turns of the series winding becomes greater. The performance approaches that of a series motor as this ratio becomes smaller.

If the load is removed from this type of motor it tends to speed up, and the counter e.m.f. increases. The current in the series field is reduced, and the greater portion of the field flux is produced by the shunt field coils. The compound motor then has characteristics similar to a shunt motor; and unlike the series motor, there is a definite no-load speed.

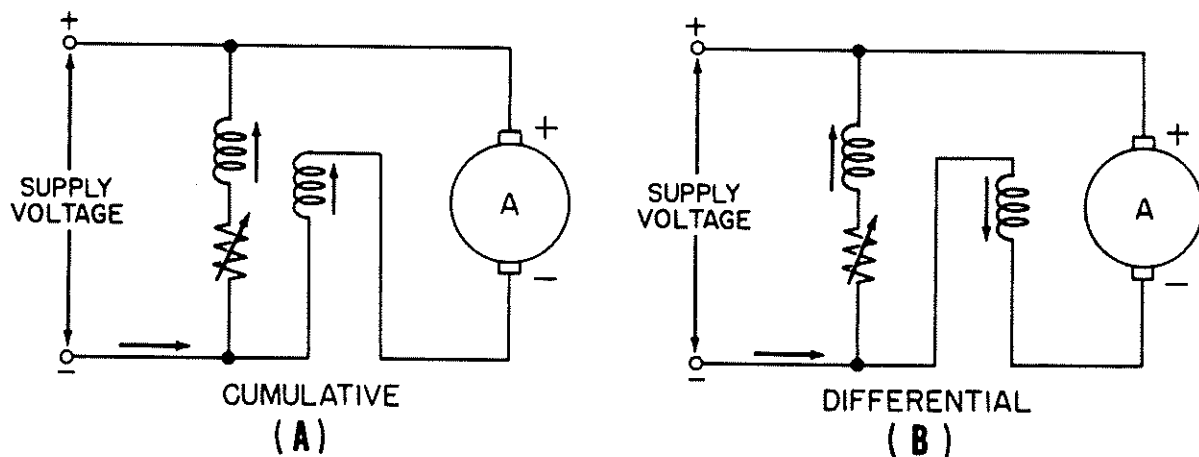


Figure 15-14.—Types of compound motors.

Because the total flux increases when there is an increase in load, there is a greater proportional increase in torque than in armature current. Therefore, for a given torque increase, this type of motor requires less increase in armature current than the shunt motor, but more than the series motor.

In some operations it is desirable to use the cumulative series winding to obtain good starting torque; and when the motor comes up to speed, the series winding is shorted out. The motor then has the improved speed regulation of a shunt motor.

In a differential compound motor, because of the opposition of the series field to the shunt field, the flux decreases as the load and armature current increase. From equation (15-9), it is seen that a decrease in flux causes an increase in speed. However, because the speed is proportional to $\frac{E_c}{\Phi}$, if both factors vary in the same proportion, the speed will remain constant. This action may occur in the differential compound motor. If more turns are added to the series coil, it is possible to cause the motor to run faster as the load is increased.

More armature current is required of the differential compound motor than of the shunt motor for the same increase in torque. This results from the fact that an increase in armature and series-field current reduces the field flux. Since the torque acting on the armature is proportional to the product of armature current and field strength, a decrease in field strength must be accompanied by a disproportionate increase in armature current in order that the product will increase.

Under heavy load the speed of the differential compound motor is unstable; and if the overload current is very heavy, the direction of rotation may be reversed. Thereafter, the motor will run as a series motor with the danger of overspeed

on no load that is the inherent characteristic of all series motors.

The characteristics of the differential compound motor are somewhat similar to those of the shunt motor, only exaggerated in scope. Thus, the starting torque is very low, and the speed regulation is very good if the load is not excessive. However, because of some of the undesirable features, this type of motor does not have wide use.

Figure 15-15 (A) shows the relative speed-load characteristics of shunt motors, cumulative compound motors, and differential compound motors. Although the speed of each of the motors is reduced when the current through the armature is increased (load is increased), the cumulative motor has the greatest decrease in speed. Likewise, in figure 15-15 (B) the cumulative motor has the greatest increase in torque with increase in load.

Cumulative compound motors are used under conditions where large starting torque is necessary, where a relatively large change in speed can be tolerated, and where the load may be removed from the motor with safety. These motors are therefore used for hoists, punches, shears, and so forth.

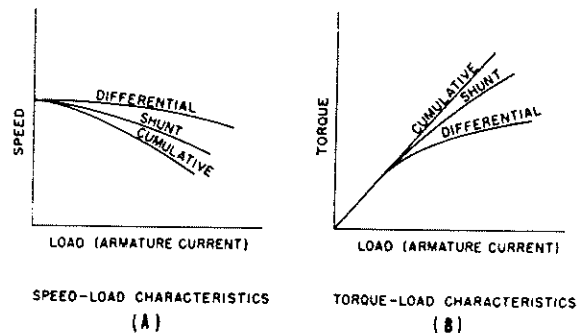


Figure 15-15.—Speed-load and torque-load characteristics of shunt and compound motors.

Manual Starters

Because the armature resistance of many motors is low (0.05 to 0.5 ohm) and because the counter e.m.f. does not exist until the armature begins to turn, it is necessary to employ an external resistance in series with the armature to keep the initial armature current to a safe value. As the armature begins to turn, the counter e.m.f. increases. Because the counter e.m.f.

opposes the applied voltage, the armature current is reduced. The resistance in series with the armature is then reduced either manually or automatically as the motor comes up to normal speed and full voltage is applied across the armature.

The relation between armature current, I_a , applied voltage E_a , counter e.m.f., E_c , armature

resistance, R_a , and starting resistance, R_s , for a shunt motor is

$$I_a = \frac{E_a - E_c}{R_a + R_s}$$

Assume that for the shunt motor shown in figure 15-16, $E_a = 100$ volts, $R_a = 0.1$ ohm, $R_s = 0.9$ ohm, and the normal full-load armature

current is 10 amperes. Without the starting resistance, the armature current would be

$$I_a = \frac{E_a}{R_a} = \frac{100}{0.1} = 1,000 \text{ amperes.}$$

This is 100 times the normal current for the motor and would obviously burn up the armature insulation and cause excessive acceleration forces.

Automatic Starters

If a motor is at a remote location, or if a large motor is to be started, it is generally desirable to use an automatic starter to bring the motor up to operating speed. Although small motors are started by means of manually operated starters, difficulties are encountered

when starting large motors. In the manually-operated starter, the skill with which the operator regulates the magnitude of the starting current is dependent upon his experience. Too much time may be taken by an overcautious operator or the maximum permissible current

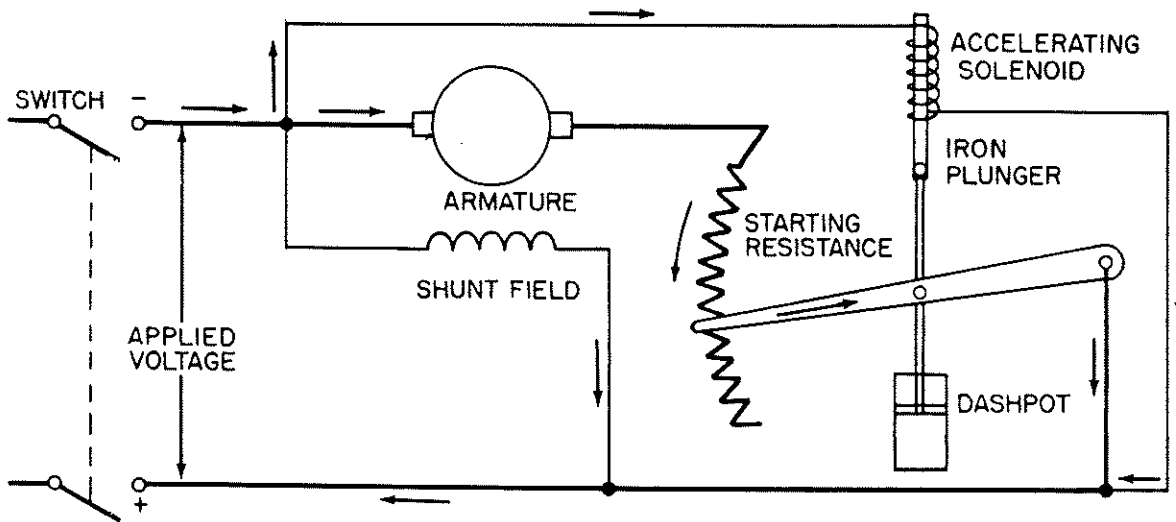


Figure 15-18.—Time-element starter.

for the motor may be exceeded by a careless one. In order that time shall not be wasted and the motor receive maximum safe current during the acceleration period, an automatic device should be used that will interpret the conditions of the load and act accordingly.

The following automatic starters will be discussed: (1) The time-element type, (2) the counter e.m.f. type, (3) the shunt current-limit type, and (4) the series current limit type.

TIME-ELEMENT STARTER

A time-element starter is one in which the resistance in series with the armature is reduced a certain amount during each succeeding

unit of time regardless of the load on the motor. One type of time-element starter is shown in figure 15-18. Initially, the full value of the starting resistance is inserted in series with the armature, and its current is therefore limited to a safe value. When the switch is closed, the full-line voltage is impressed across the accelerating solenoid and across the shunt field. The solenoid immediately begins to draw the iron core upwards, and the starting resistance is gradually cut out of the armature circuit. The speed with which the resistance is cut out depends on the size of the orifice (the hole through which the oil flows) in the dashpot. The smaller the orifice, the greater the time delay. The time delay should be such that as

the speed and the counter e.m.f. builds up, the starting current is maintained at the maximum safe value during the accelerating period. During the time required to reach full speed, the resistance is completely removed from the circuit.

The advantages of the time-element type of automatic starter are that its cost is low, the wiring is simple, and starting is generally sure. The disadvantages are that the amount of load cannot be sensed — that is, the resistance is removed at the same rate whether the load is heavy or light, the motor is not protected on overload, and the dashpot is a source of trouble.

COUNTER E.M.F. STARTER

The counter e.m.f. starter depends for its operation on the counter e.m.f. developed across the armature. As may be seen from figure 15-19 (A), the solenoid that activates the contacts is connected directly across the armature. It therefore responds to armature voltage, which is only slightly higher than the counter e.m.f.

At start (fig. 15-19 (B)), time t_0 , the armature current flowing through the starting resistance causes a reduced voltage to be applied to the armature and the accelerating contactor will not immediately close its contacts due to low voltage across its operating coil. As the motor accelerates, the rising counter e.m.f. causes the armature current and voltage drop across the starting resistance to reduce. At the same time, the voltage across the armature increases. When this voltage rises to the proper value, time t_1 , the accelerating contactor closes and shorts out the starting resistance, thus applying full voltage across the armature. The accompanying increase in starting current causes continued acceleration until the motor comes up to rated speed, and the armature current is again reduced to the normal value. For simplicity, only one resistor and starting contactor are shown, although large motors usually employ several contactors and several steps of starting resistance. If the load is heavy, the acceleration is slower and the rise in voltage on the accelerating contactor operating coil is delayed so that the starting resistance is not cut out until the rise in speed and counter e.m.f. permits the contactor to close.

The advantages of the counter e.m.f. starter are that the load is interpreted and the resistance cut out accordingly, the cost is low, the wiring is simple, and the dashpot is not used.

The disadvantages of the counter e.m.f. starter are that if the line voltage varies, the acceleration may become erratic. For example, if the line voltage rises, the starting resistance may be removed too soon; and if it falls, the starting contactor may not be activated at all. The starting contactor coils are designed to close the contactor on one value of voltage and to operate continuously on an increased voltage. Thus, they are sensitive to voltage change and will not operate properly if line voltage fluctuations occur.

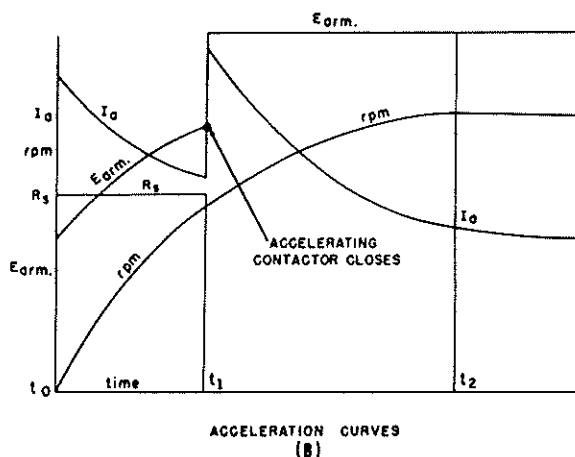
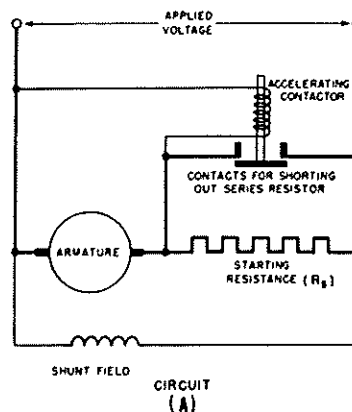


Figure 15-19.—Counter e.m.f. starter.

SHUNT CURRENT-LIMIT STARTER

The disadvantages of the counter e.m.f. starter are overcome in the shunt current-limit starter. This motor starter employs accelerating contactors with shunt-type operating coils wound for full-line voltage. Each contactor includes an interlocking series relay, the operation of which

is limited by the motor starting current. When the series relay closes its contacts, the shunt operating coil of the accelerating contactor is energized and a section of starting resistance is cut out of the armature circuit. This type of motor starter thus derives its name from the fact that the accelerating contactors are shunt operated and the closure of the series relays is limited by the magnitude of the armature current.

Figure 15-20 is a simplified schematic diagram of a shunt current-limit starter operating in connection with a pushbutton starter with no-voltage release holding-contacts. When the ON button is pressed down momentarily, the no-voltage release coil is energized. The holding relay contacts and the line contacts are closed. The series relay is mechanically released, and its contacts would close were it not for the fact that the armature current flows through the series coil and holds its core up, thus keeping its contacts open. Thus, it may be seen that current flows from the negative terminal of the voltage source through the armature, through the starting resistor, through the series relay coil, and back to the positive terminal of the voltage source.

As the motor speeds up, the counter e.m.f. increases, and the armature current is reduced accordingly. The field of the series relay is thereby weakened and the relay contacts are

closed. This action energizes the coil of the accelerating contactor and its contacts close, thus shorting out the starting resistor and the series relay. The full-line voltage is then safely applied across the armature. The series relay and accelerating contactor contacts remain closed until the line contacts are opened.

When the OFF button is pressed, current through the no-voltage release coil is interrupted and the holding relay contacts, the line contacts, and the series relay contacts are opened. Line voltage is thus removed from the motor.

Although for simplicity only one starting resistor is shown in a practical system, two or three are commonly used. Additional accelerating contactors and interlocking series relays are then used to remove the starting resistance in steps as the motor comes up to speed.

The advantage of the shunt current-limit starter is that starting resistance is cut out of the armature circuit only after the speed has built up and the motor current has been reduced to a safe value irrespective of line voltage fluctuations. If the load is too great for the motor to accelerate normally, the counter e.m.f. cannot build up sufficiently to reduce the current through the series relay to cause its contacts to fall closed. Therefore, the starting resistance remains in the circuit and the armature is protected against excessive current.

The disadvantage is that the accelerating units are complicated and expensive.

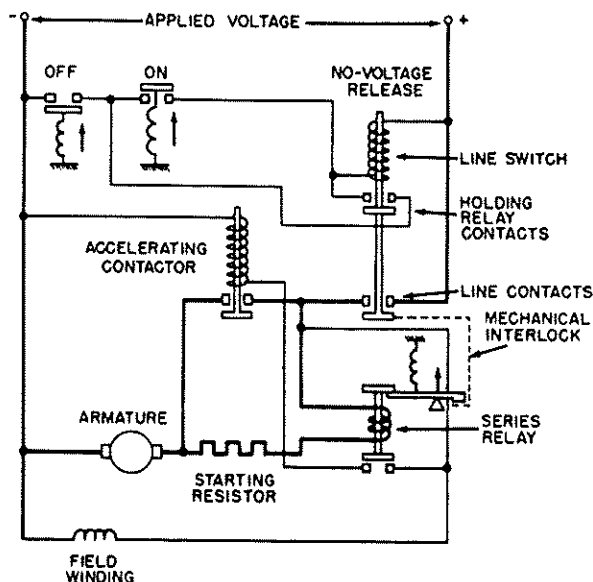


Figure 15-20.—Shunt current-limit starter.

SERIES CURRENT-LIMIT STARTER

The series current-limit type of motor starter was designed to accelerate motors and to provide the same protection afforded by the shunt current-limit type of starter, but to do the job with less complicated equipment. The interlocking series relays are omitted and the accelerating contactors are designed to lock open on the initial in-rush of starting current. When the current falls to a predetermined value the contactor closes and shorts out the starting resistance.

In the series current-limit starter, the relay coil which operates the accelerating contactor is series wound — that is, it is connected in series with the armature circuit. The simplified circuit, showing only one starting resistor, is shown in figure 15-21 (A).

One type of magnetically operated switch that makes this type of starter possible is shown in figure 15-21 (B). The initial current

DIRECT CURRENT MOTORS

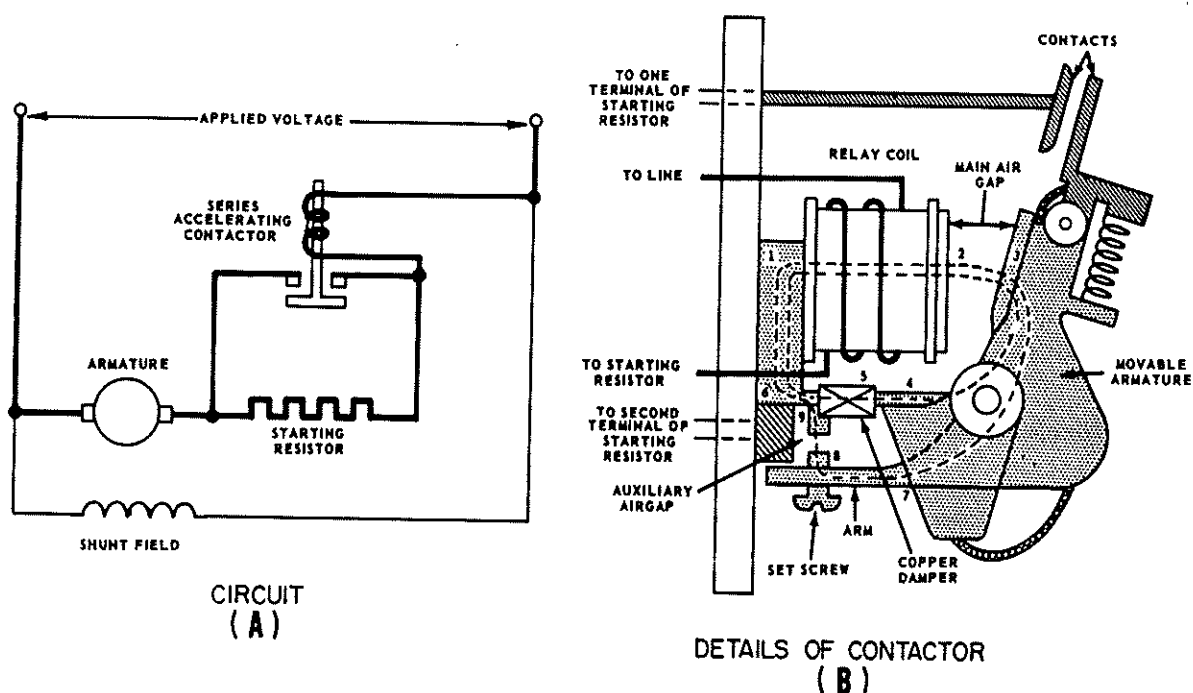


Figure 15-21.—Series current-limit starter.

through the coil causes the accelerating contactor to lock open. When the current falls to a certain predetermined value, the switch will close.

The coil is wound with a few turns of heavy wire. When current flows through the coil, the movable armature is acted upon by two forces, one across the main air gap, the other across the auxiliary air gap. The force across the main air gap tends to close the contactor; that across the auxiliary air gap tends to open it. The flux paths are first 1, 2, 3, 4, 5, 6, 1; and second 1, 2, 3, 7, 8, 9, 6, 1. The first path includes only the main air gap. The second includes both gaps. When a small amount of current flows through the coil, the flux path is principally through 1, 2, 3, 4, 5, and 6 and the force exerted across the main air gap tends to close the switch. When a large amount of current flows through the coil, the flux path is through 1, 2, 3, 7, 8, and 9. This path includes both the main and auxiliary air gaps. Because the auxiliary gap is smaller, the force exerted across this gap to

hold the contactor open exceeds the force across the main gap to close it and the contactor locks open.

To prevent the flux from rushing through the shorter path, 4, 5, 6, and closing the contactor before it has time to lock open, a short-circuited coil (damper) is placed around this flux path, as shown in figure 15-21 (B). As the flux links this coil, the induced current in the copper damper sets up a counter magnetomotive force that opposes the original flux and causes it to take the path through 7, 8, and 9 during the time that the current is rising. When the series operating coil current levels off at a high value, the flux path 4, 5, and 6 becomes saturated and sufficient flux is established through 7, 8, and 9 to maintain the contactor in the locked-out condition.

This type of contactor is especially satisfactory when the motor is always under load. The principal disadvantage is that the switch may drop open on light load. However, a shunt holding coil may be used to prevent this.

Motor Efficiency

The efficiency of any type of machine is the ratio of the output power to the input power. This ratio is commonly expressed as a percent. Because all machines have some losses, the efficiency will never be 100 percent. Expressed as a percentage, efficiency becomes

$$\text{efficiency} = \frac{\text{output}}{\text{input}} \times 100,$$

or

$$\text{efficiency} = \frac{\text{output}}{\text{output} + \text{losses}} \times 100,$$

$$\text{efficiency} = \frac{\text{input} - \text{losses}}{\text{input}} \times 100.$$

The first equation is general. The second is advantageous when applied to electric generators and transformers. The third is most useful when applied to electric motors. The output must be expressed in the same units as the input. For example, if the output is expressed in horsepower and the input is expressed in watts, they can be changed to common units by means of the relation,

$$746 \text{ watts} = 1 \text{ horsepower.}$$

There are various types of mechanical and electrical losses in d-c motors, some of which are common to other types of motors.

One loss is in BEARING FRICTION. This type of friction is reduced by proper oiling. Roller bearings have less friction loss than sleeve bearings. However, at excessive speed or under excessive load the loss due to bearing friction may be appreciable. A loss is also introduced by BRUSH FRICTION. This may be reduced by the use of a well-polished commutator and properly fitted brushes. WINDAGE LOSS is that due to the resistance of the air to a rapidly revolving armature. IRON LOSSES include eddy-current loss and hysteresis in the armature iron. COPPER LOSSES include the I^2R loss in the armature and field windings.

As an example, assume that the motor shown in figure 15-22 is supplied with 10 amperes at 100 volts.

The COPPER LOSS in the field is

$$I_f^2 \times R_f = 1^2 \times 100 = 100 \text{ watts.}$$

The armature current is 10 - 1, or 9 amperes and the COPPER LOSS in the armature is

$$I_a^2 \times R_a = 9^2 \times 1 = 81 \text{ watts.}$$

Assume that the total MECHANICAL LOSS (friction, windage, and so forth) is 90 watts. The TOTAL LOSS is therefore 271 watts.

The input is

$$E_a \times I_L = 100 \times 10 = 1,000 \text{ watts.}$$

The output is

$$\text{input} - \text{losses} = 1,000 - 271 = 729 \text{ watts.}$$

The efficiency is

$$\frac{\text{output}}{\text{input}} \times 100 = \frac{729}{1,000} \times 100 = 72.9 \text{ percent.}$$

If it is determined (by means of a prony brake test) that the power developed by the motor is 0.976 horsepower, the efficiency is also determined as

$$\begin{aligned} \text{efficiency} &= \frac{\text{output}}{\text{input}} \times 100 \\ &= \frac{0.976 \times 746}{1,000} \times 100 = 72.9 \text{ percent.} \end{aligned}$$

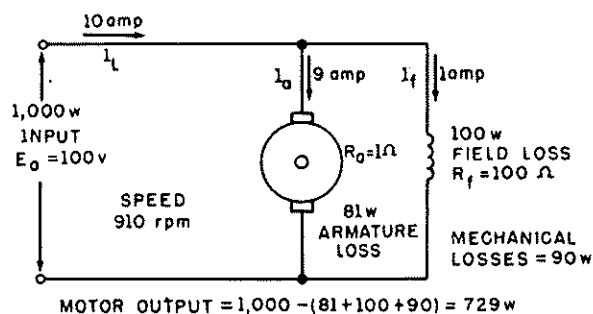


Figure 15-22.—Distribution of losses in a motor.

Speed Control

The speed, N , of a d-c motor is directly proportional to the armature counter e.m.f., E_c , and inversely proportional to the field strength, Φ .

Transposing equation (15-8) for N , $N = \frac{E_c 10^8 p}{\Phi Z P}$.

Such factors as the numbers of poles, P , the number of current paths, p , and the total number of armature conductors, Z , can be lumped into a single constant, K . Simplified, the expression becomes

$$r.p.m. = \frac{KE_c}{\Phi}$$

In a shunt motor

$$E_c = E_a - I_a R_a$$

and

$$r.p.m. = \frac{K(E_a - I_a R_a)}{\Phi} \quad (15-11)$$

where E_a is the voltage applied across the armature. This is similar to, but not identical with, equation (15-9) for a series motor.

From equation 15-11, it is seen that the speed may be INCREASED by DECREASING the field strength, and vice versa, or the speed may be increased by increasing E_a , and vice versa. Practically, these variations are most simply accomplished by inserting a field rheostat in series with the field circuit, or a variable resistor in series with the armature circuit.

SPEED CONTROL BY ARMATURE SERIES RESISTANCE

Figure 15-23 shows how speed control may be accomplished by means of a variable resistor in series with the armature. The circuit is the same as that used in the motor starter circuit in figure 15-16. However, the wattage rating is different. The starting resistance should only be inserted for a short interval, whereas the speed control resistance can remain in the circuit indefinitely.

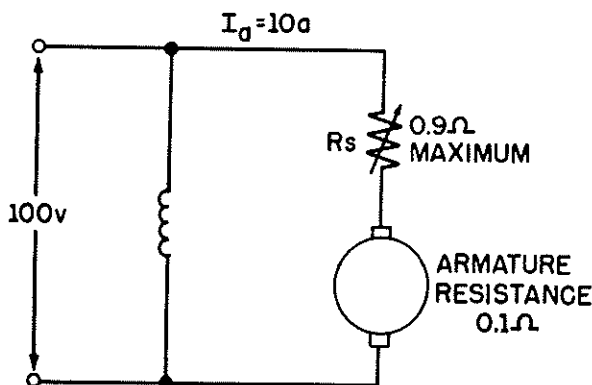


Figure 15-23:—Speed control by means of armature series resistor.

In the example of the motor shown in figure 15-23, assume that $\frac{K}{\Phi}$, as indicated in the previous equation, is replaced by the number 10. The equation for speed in r.p.m. then becomes

$$r.p.m. = 10[E_a - I_a(R_s + R_a)]$$

When R_s is set at zero, the resistance, R_a , offered by the armature is 0.1 ohm, and I_a is assumed to be 10 amperes. Therefore,

$$r.p.m. = 10[100 - 10(0 + 0.1)] = 990.$$

When R_s is increased to 0.1 ohm, I_a is lowered. The motor speed is reduced, the counter e.m.f. is reduced, and I_a is assumed to come back to the original value of 10 amperes. At the stable condition, the new speed is

$$r.p.m. = 10[100 - 10(0.1 + 0.1)] = 980.$$

The rheostatic losses involved in this method of speed control are appreciable at low speeds and the resultant reduction in efficiency makes this type of control undesirable if the motor is to be operated at greatly reduced speed for prolonged intervals.

SPEED CONTROL BY ADJUSTING THE FIELD STRENGTH

A more economical method of speed control is by rheostatic adjustment of the field current. If the field strength is weakened, the speed of the motor is increased; and if the strength of the field is increased, the speed of the motor is decreased.

Figure 15-24 indicates a method of varying the strength of the field by means of a field rheostat. When the field rheostat is cut out, the field current is 1 ampere. The counter e.m.f. is 90 volts, and the armature current is 10 amperes. The MEASURED speed is 900 r.p.m. When the resistance of the field rheostat is increased to 11.1 ohms, the field current is reduced to 0.9 amperes and the field flux is reduced. This causes a reduction in counter e.m.f. and a sharp increase in armature current, which causes an increase in force on the armature and an increase in armature speed. As the speed builds up, the counter e.m.f. builds up to 90 volts again, and the armature current is again reduced to 10 amperes.

The speed corresponding to a field current of 0.9 ampere may be computed if it is recalled that the speed varies inversely with the flux and that the flux (below saturation) varies directly with the current. Thus, if the speed is 900 r.p.m. when the field current is 1 ampere it will be $900 \times \frac{1}{0.9} = 1,000$ r.p.m. when the field current is 0.9 ampere.

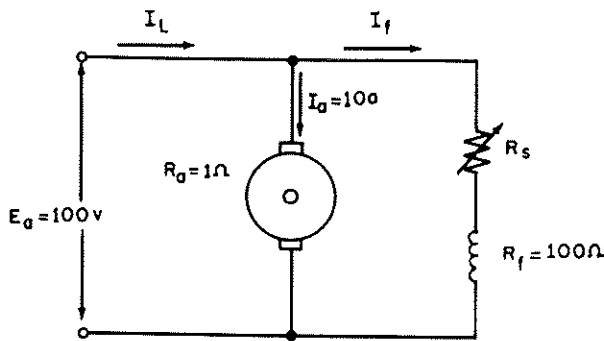


Figure 15-24.—Speed control by varying the strength of the field.

SPEED CONTROL BY WARD-LEONARD SYSTEM

As has been explained in the previous paragraphs, the speed of a d-c motor can be controlled by at least two methods—either the armature voltage can be varied, as in figure 15-23 or the field voltage can be varied as in figure 15-24. The first method gives a range of speeds below the rated full-load speed. The second, gives a range of speed above the rated full-load speed. The first method takes away the constant speed characteristics from the shunt motor when the load varies. The second method permits control with a physically smaller resistor and greatly reduced power and gives essentially constant speed characteristics at any speed setting of the field rheostat provided the field is not weakened excessively. With a very weak field the motor may stall. The inherent difficulties of both methods are removed by the Ward-Leonard method shown in figure 15-25.

The d-c motor armature whose speed is to be controlled, is fed directly from a d-c generator armature which is driven by a constant-speed

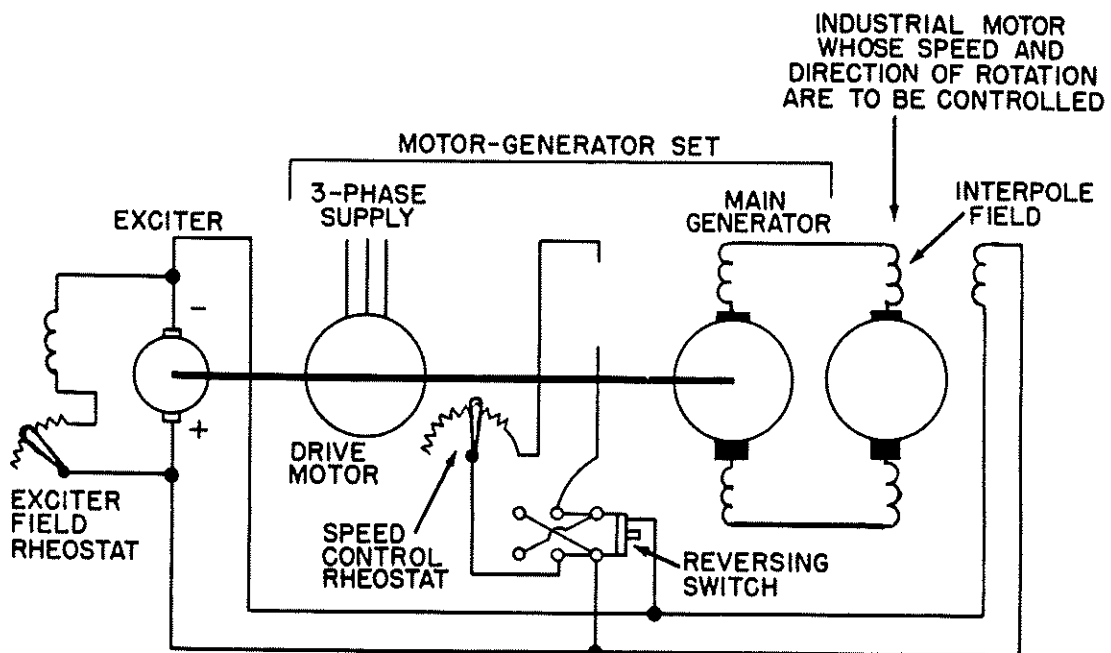


Figure 15-25.—Ward-Leonard speed control system.

prime mover. The d-c field supply to the generator is variable in both magnitude and polarity by means of a rheostat and reversing switch, as shown. Therefore, the motor armature is supplied by a generator having smoothly varying voltage output from zero to full-load value. The motor field is supplied with a constant voltage from the same source as that supplying the generator fields. The generator drive power could be from a single-phase or three-phase a-c motor, from an engine, or other constant-speed source. In the same way, the d-c supply can be supplied from a rectifier, from an exciter on the end of the generator shaft, or from any other suitable d-c source. In the figure

the field exciter is a direct-connected unit on the shaft of the motor-generator set. The drive motor for the M-G (MOTOR-GENERATOR) set is shown as a 3-phase motor. Both the main generator and the speed-control motor have commutating poles, and in some instances, compensating windings.

The advantages of this type of speed control are that it does away with the armature rheostatic losses and instability of speed with variable loads.

The disadvantage of this method of speed control is the initial expense of the added equipment—that is, the M-G set with its control equipment.

QUIZ

- The most convenient method of determining the direction of induced motion of a current-carrying conductor in a magnetic field is by
 - applying the right-hand rule for motors
 - applying the left-hand rule for motors
 - using a small permanent magnet
 - observation of the location of the conductor
- The formula for torque developed by a motor is
 - $T = \frac{K_t}{\Phi I_a}$
 - $T = K_t^2 \Phi I_a$
 - $T = K_t \Phi I_a^2$
 - $T = K_t \Phi I_a$
- The effective voltage (E_{eff}) drop in a motor's armature is determined by
 - $E_{eff} = E_{app} + c.e.m.f.$
 - $E_{eff} = E_{app} \times c.e.m.f.$
 - $E_{eff} = E_{app} - c.e.m.f.$
 - $E_{eff} = \frac{c.e.m.f.}{E_{app}}$
- Which of the following is true, regarding the speed regulation of a shunt motor?
 - It has a constant-speed characteristic under varying loads
 - It has a varying speed characteristic under varying loads
 - It has a varying speed characteristic under constant loads
 - None of the above are correct
- The primary advantage of the differentially compounded motor is that
 - it is stable under heavy loads
 - its speed regulation is very good if load is not excessive
 - it has good speed regulation under varying loads
 - it will start under a heavy load
- If the no-load speed of a shunt motor is 1,800 r.p.m. and the full-load speed is 1,475 r.p.m., the speed regulation is
 - 18%
 - 22%
 - 2.2%
 - 1.8%
- The input power of a series motor is the product of the applied voltage and
 - counter e.m.f.
 - torque
 - current through the armature and the field
 - current through the armature and counter e.m.f.
- The disadvantage of the time-element automatic starter is that the
 - cost is high
 - wiring is complicated
 - construction is too heavy to be practical
 - motor is not protected on overload
- The starting resistor of the shunt current-limit starter is connected in
 - parallel with the motor armature
 - series with the accelerating contactor
 - series with the field winding of the motor
 - series with the armature of the motor

BASIC ELECTRICITY

10. A motor which has an output of 820 watts and an input of 960 watts has an efficiency of approximately
 - a. 90%
 - b. 85%
 - c. 75%
 - d. 70%
11. The horsepower developed by a motor depends mainly upon which of the following two factors?
 - a. Speed and voltage
 - b. Speed and torque
 - c. Torque and voltage
 - d. Torque and watts
12. A series motor is more adaptable where a
 - a. small variation of torque and speed is needed
 - b. wide variation of torque but a small variation of speed is needed
 - c. wide variation of torque is required, and wide variations in speed are allowable
 - d. constant speed is needed
13. Cumulative compound motors are best suited for use where
 - a. small starting torque is required
 - b. small changes in speed can be tolerated
 - c. the load may be removed from the motor with safety
 - d. constant speed under varying load is required
14. What is the output power in watts of a shunt motor of 1 horsepower operating on 100 volts at 910 r.p.m., armature current of 9 amps., and a line current of 10 amps.?
 - a. 98.4 watts
 - b. 472 watts
 - c. 646 watts
 - d. 815 watts
15. The counter e.m.f. of a motor is zero when the
 - a. motor is at rated speed
 - b. armature is not turning
 - c. motor is almost up to rated speed
 - d. armature has just begun to turn
16. The operation of the c.e.m.f. starter depends upon the
 - a. size of the orifice in the dashpot
 - b. c.e.m.f. developed across the armature
 - c. accelerating contacts
 - d. interlocking relays
17. In a shunt current-limit starter the number of starting resistors that are commonly used is
 - a. one
 - b. two or three
 - c. five or six
 - d. more than ten
18. The speed of a motor with no load, with an increase of resistance in series with the field winding, will
 - a. not be affected
 - b. decrease
 - c. increase
 - d. fluctuate rapidly
19. The generated voltage (c.e.m.f.) of a motor
 - a. opposes the impressed (source) voltage
 - b. opposes any change in load
 - c. aids the impressed (source) voltage
 - d. none of the above are correct
20. When a load is applied to a shunt motor, which one of the following will happen?
 - a. Speed decreases—c.e.m.f. goes up
 - b. Speed increases—c.e.m.f. goes down
 - c. Speed increases—c.e.m.f. goes up
 - d. Speed decreases—c.e.m.f. goes down
21. On a time-element starter what determines the speed with which the resistance is cut out?
 - a. Size of the orifice in the dashpot
 - b. Counter e.m.f. of the armature
 - c. Interlocking relays
 - d. Accelerating contacts
22. The coil of the accelerating contactor of the shunt current-limit starter is caused to become energized by which of the following when the motor speeds up?
 - a. Series relay contacts closing
 - b. Series relay contacts opening
 - c. The no-voltage release
 - d. Holding relay contacts
23. In the series current-limit starter the flux is prevented from closing the contactor before it has time to lock open by
 - a. an open coil
 - b. the spring tension of the contacts
 - c. starting resistor
 - d. a short-circuited coil
24. The d-c motor armature whose speed is to be controlled by the Ward-Leonard system is fed by a
 - a. 3-phase motor
 - b. d-c supply in parallel with a rheostat
 - c. d-c generator
 - d. rectifier

CHAPTER 16

ELECTRICAL DRAWINGS AND TECHNICAL MANUALS

This course has presented the basic principles of electricity. These principles are widely applicable. For instance, the laws of voltage distribution around a closed circuit apply equally to a-c and d-c circuits irrespective of the number of voltage sources or the nature of the components of the circuit. When analyzing the operation of even the most complex circuit or equipment, the principles of its functions may be explained by one or more of the widely applicable electrical laws. Thus, the first step in your technical training is learning these laws, most of which are set forth in the preceding parts of this text. The second step, gained largely through experience, is learning the methods and practices by which these principles are put to work, in the form of actual hardware, in hundreds of different types of equipment.

One of the best ways to learn these methods and common practices is to become familiar with the language of practical electricity. This language is found in the technical manual (instruction book) written for each equipment and in the diagrams for each system. You cannot hope to memorize every detail of every circuit in the

complex systems and equipments you must maintain. A good technician does not even attempt it. Instead, you should be able to obtain this information as you need it from the manuals and drawings provided for that purpose. To do this, you must be able to read electrical drawings and diagrams. The ability to read a particular drawing, coupled with the basic principles of electricity, will make it much easier for you to understand, adjust, operate, and repair any particular equipment or circuit.

In the construction of a wiring or schematic diagram of a circuit or system, it would not be practical, and rarely even useful, to draw pictures of each part as they actually appear. Instead, each part in a wiring or schematic diagram is represented by a symbol. Electrical symbols are to the technician as shorthand is to the stenographer. All parts, such as resistors, capacitors, switches, relays, and so forth, have symbols that are standard. The most important ability in reading electrical drawings is the ability of the technician to form a mental correlation between the symbol for a part as it appears in a diagram, and the actual appearance and function of that part.

Electrical Symbols

Table 16-1 is a listing of some of the most common standard electrical parts. The name and standard symbol for each part are given, along with a picture. By studying this list, and others similar to it, you will be able to mentally correlate parts and their symbols, which is necessary in developing the ability to read electrical diagrams.

A brief discussion of some of the most common parts that are used in electrical circuits follows the list of symbols.

RESISTOR COLOR CODING

As you probably know, a resistor is a device used to limit current flow. Resistors are of two types: fixed and variable. Fixed resistors may be made of wire wound on a core and coated with ceramic or they may be made of carbon. The majority of fixed resistors have axial leads. Resistance value is indicated by 3 colored bands. A fourth band is sometimes used to indicate tolerance as follows: gold = ± 5 percent, silver = ± 10 percent. When no fourth band is present,

BASIC ELECTRICITY

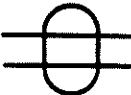
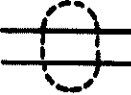
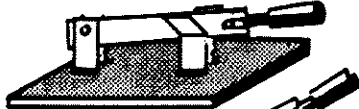
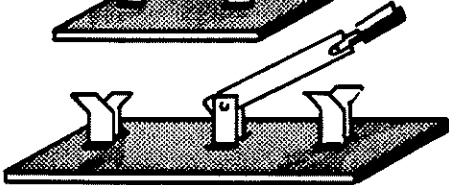
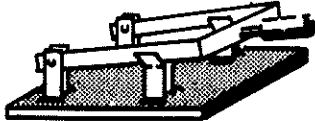
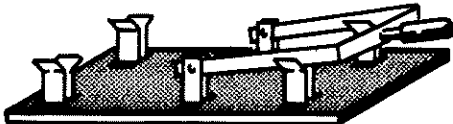
Name	Symbol	Picture
CONNECTION		
NO CONNECTION		
GROUND		
TWO-CONDUCTOR CABLE		
SHIELDED TWO-CONDUCTOR CABLE		
COAXIAL CABLE		
SINGLE POLE SINGLE THROW SWITCH		
SINGLE POLE DOUBLE THROW SWITCH		
DOUBLE POLE SINGLE THROW SWITCH		
DOUBLE POLE DOUBLE THROW SWITCH		

Table 16-1. - Electrical symbols.

ELECTRICAL DRAWINGS AND TECHNICAL MANUALS

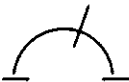
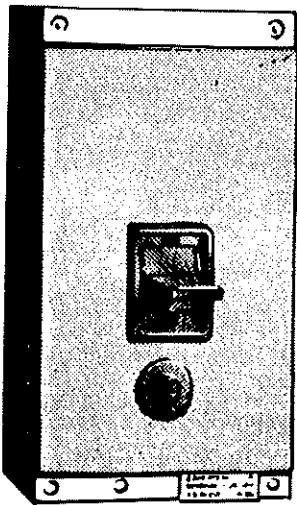
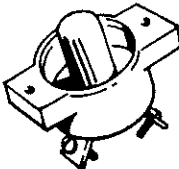
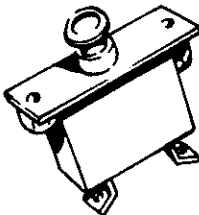
Name	Symbol	Picture
SWITCH CIRCUIT BREAKER		
PUSH CIRCUIT BREAKER		
PUSH-PULL CIRCUIT BREAKER		
FUSE		
LAMP		
CELL (LONG VERTICAL LINE IS ALWAYS POSITIVE)		

Table 16-1. - Electrical symbols - Continued

BASIC ELECTRICITY

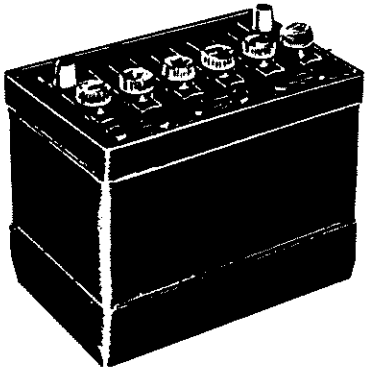
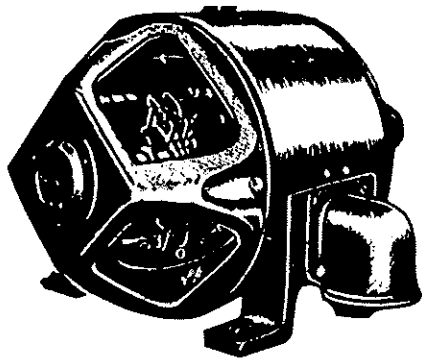
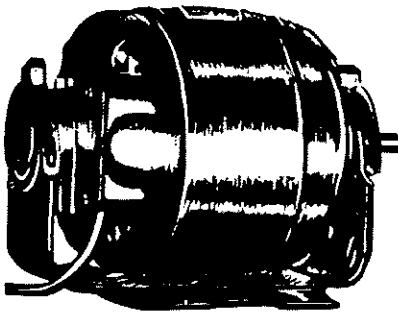
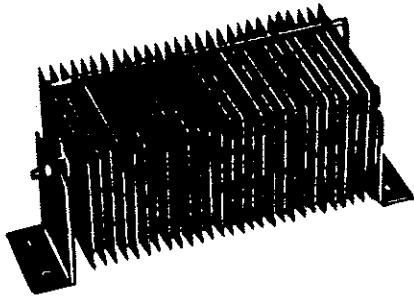
Name	Symbol	Picture
BATTERY		
GENERATOR (MAY BE A-C OR D-C, DEPENDING ON HOW LABELED)		
MOTOR (MAY BE A-C OR D-C DEPENDING ON HOW LABELED)		
METALLIC RECTIFIER		

Table 16-1. - Electrical symbols - Continued

ELECTRICAL DRAWINGS AND TECHNICAL MANUALS

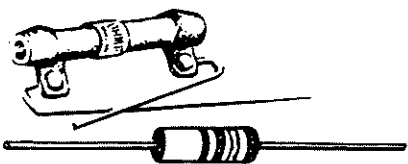
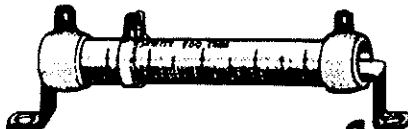
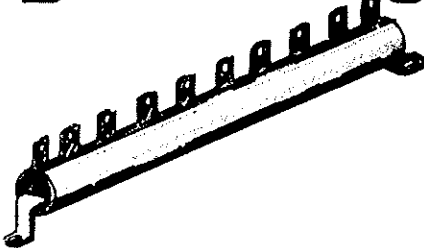
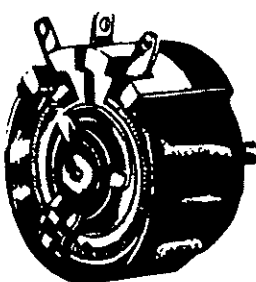
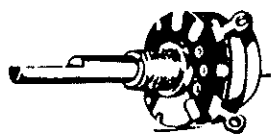
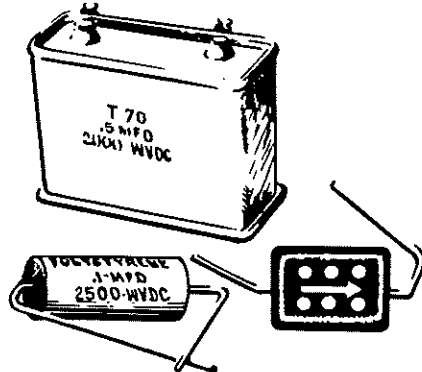
Name	Symbol	Picture
RESISTOR		
VARIABLE RESISTOR		
TAPPED RESISTOR		
POTENTIOMETER		
RHEOSTAT		
CAPACITOR, FIXED		

Table 16-1. - Electrical symbols - Continued

BASIC ELECTRICITY

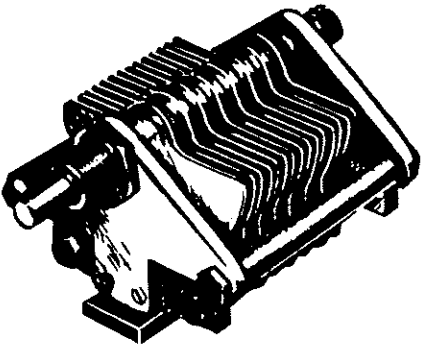
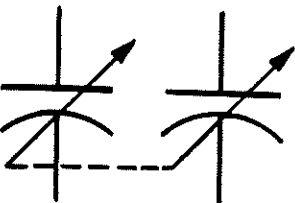
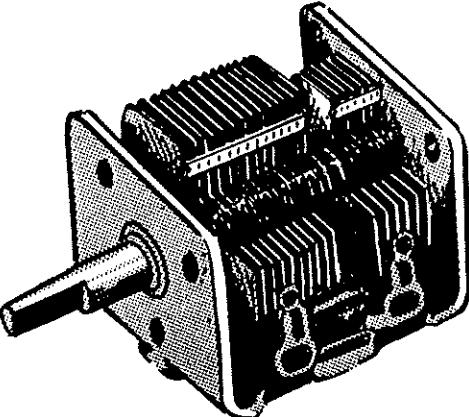
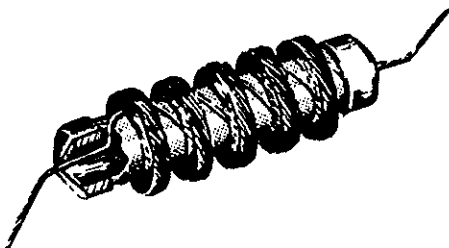
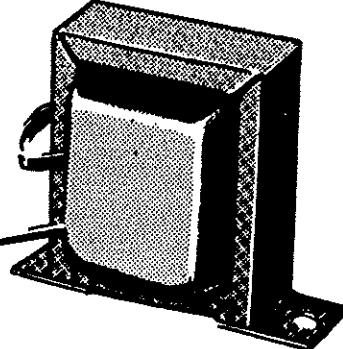
Name	Symbol	Picture
CAPACITOR, VARIABLE		
CAPACITOR, GANGED		
INDUCTOR, AIR CORE		
INDUCTOR, IRON CORE		

Table 16-1. — Electrical symbols — Continued

ELECTRICAL DRAWINGS AND TECHNICAL MANUALS

Name	Symbol	Picture
TRANSFORMER, AIR CORE		
TRANSFORMER, IRON CORE		
RELAY COIL WITH CONTACTS		
PIEZOELECTRIC CRYSTAL UNIT		

Table 16-1. - Electrical symbols - Continued

BASIC ELECTRICITY

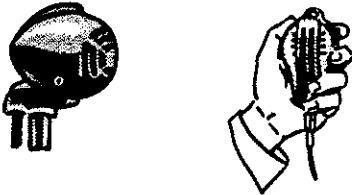
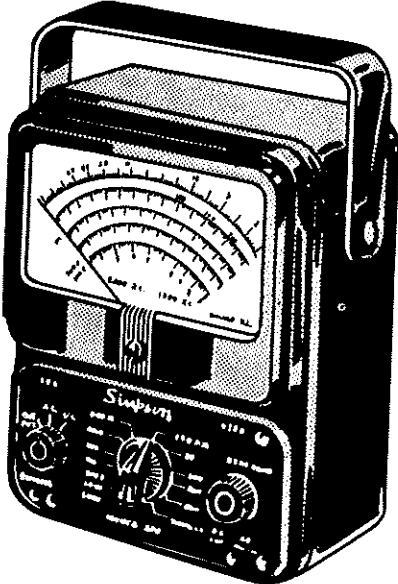
Name	Symbol	Picture
HEADPHONES		
MICROPHONE		
LOUDSPEAKER		
VOLTMETER		
AMMETER		
OHMMETER		

Table 16-1. - Electrical symbols - Continued

ELECTRICAL DRAWINGS AND TECHNICAL MANUALS

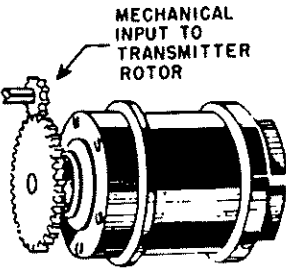
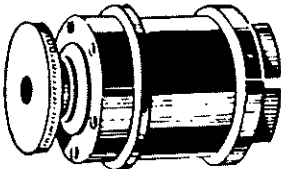
Name	Symbol	Picture
THERMAL RESISTOR (BALLAST LAMP)		
VOLTAGE REGULATOR OR GLOW TUBE (d-c TYPE)		
GLOW LAMP (COLD CATHODE) a-c TYPE		
SYNCHRO TRANSMITTER RECEIVER OR CONTROL TRANSFORMER		
DIFFERENTIAL TRANSMITTER OR RECEIVER		

Table 16-1. - Electrical symbols - Continued

BASIC ELECTRICITY

the resistor has a ± 20 percent tolerance. For example, colored bands of red, orange, blue, and gold would indicate that the value of the resistor was 23 megohms (23,000,000 ohms) with a resistance tolerance of ± 5 percent. (See fig. 16-1 and table 16-2.)

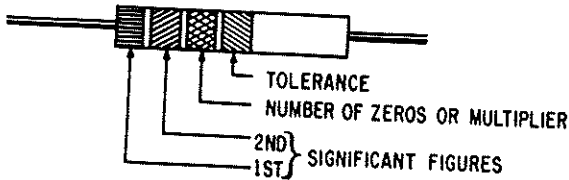


Figure 16-1.—Standard resistor coding.

Some fixed resistors are constructed with radial leads as shown in figure 16-2. The method of interpreting the color code to determine the value of these resistors is somewhat different from the method used with axial-lead resistors. (See fig. 16-2.) For example, if the body of the resistor is brown, end B is green, and dot C is yellow, the resistor will have a resistance of 150,000 ohms with a tolerance of 20% (no band D indicated).

COLOR	
Body A	Indicates first significant figure of resistance value in ohms.
End B	Indicates second significant figure.
C (dot or band)	Indicates multiplier.
Band D	If any, indicates tolerance in percent. If no color appears in this position, tolerance is 20%.

Figure 16-2.—Color coding for radial-lead resistors.

Variable resistors are of two general types: rheostats and potentiometers.

A rheostat is a variable resistor which is normally used to adjust the current in a circuit without opening the circuit; however, some rheostats are constructed so that the circuit may also be opened. Generally, a rheostat has two terminals; one terminal is connected to one end of the resistance element, and the other terminal to the sliding contact. (See fig. 16-3.) As shown in this figure, the resistance element is circular in shape and is made of resistance wire wound around an insulating form usually made of a ceramic material. The resistance is decreased by rotating the wiper toward the end contact.

The potentiometer (often called a "pot") is a control device used to vary the amount of voltage applied to an electrical device. The term

Color	Significant figure or number of zeros	Decimal multiplier	Resistance tolerance
BLACK	0	---	Percent $\pm$
BROWN	1	---	---
RED	2	---	---
ORANGE	3	---	---
YELLOW	4	---	---
GREEN	5	---	---
BLUE	6	---	---
VIOLET	7	---	---
GRAY	8	---	---
WHITE	9	---	---
GOLD	---	0.1	5(J)*
SILVER	---	0.01	10(K)*
NO COLOR	---	---	20(M)*

* SYMBOL DESIGNATION ALTERNATE FOR COLOR

Table 16-2. — Standard color code for resistors.

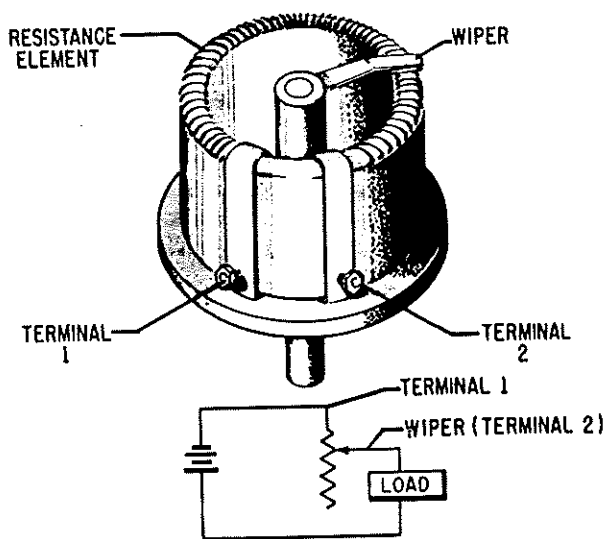


Figure 16-3.—Rheostat.

potentiometer is usually used to refer to any adjustable resistor having three terminals, two of which are connected to the ends of the resistance element and the third to the wiper contact. (See fig. 16-4.) By positioning the sliding contact, any desired voltage within the range of the

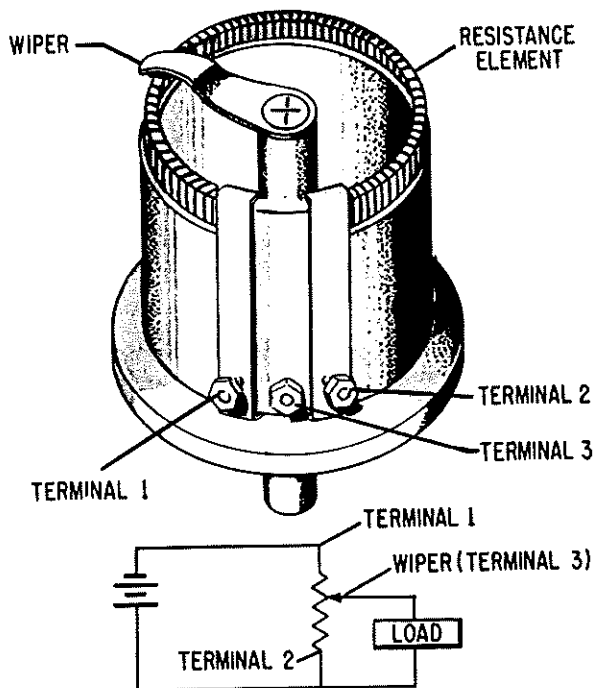


Figure 16-4.—Potentiometer.

potentiometer may be "picked off" and used where needed. As a rule, potentiometers are constructed to carry smaller currents than rheostats.

Resistors are rated according to the heat they will safely dissipate. Heat is produced by current flow through a resistance; and as current increases, the temperature will rise. The watt is a unit of power and it represents the power expended in heat as current flows through the resistor:

$$P = I^2 R$$

where P is the number of watts; I , the current flow through the resistor; and R , the resistance of the resistor.

The wattage rating of resistors is dependent on both the composition of the resistor and the physical size; as resistor size increases, wattage rating increases. Resistors used in Navy equipment usually have a wattage rating of at least 50 percent above the wattage that can be expected to be developed across them. For example, 5 watts would be developed across a 5-megohm resistor if 1 milliamperes of current flowed through it.

$$P = I^2 R$$

$$P = (1 \times 10^{-3})^2 \times 5 \times 10^6$$

$$P = 1 \times 10^{-6} \times 5 \times 10^6 = 5 \text{ watts}$$

Thus, this resistor should have a wattage rating of at least 7.5 watts.

Carbon resistors generally have a wattage rating of one-half to two watts. For wattage ratings of more than two watts, wire-wound resistors are generally used.

CAPACITOR COLOR CODING

The various types of capacitors were described in chapter 9 of this training course. Many capacitors are stamped with their working voltage and their value of capacitance. The capacitance is given in microfarads. (See fig. 16-5.) When the value of capacitance is not stamped on capacitors, it is indicated by the use of a color code as shown in table 16-3. On molded capacitors, colors are applied in the form of dots, four different marking systems being

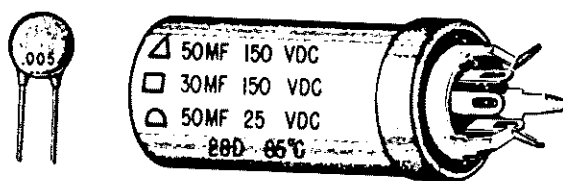


Figure 16-5.—Capacitors stamped with value of capacitance.

Color	Capacitance		Tolerance
	Significant figure	Multiplier	
BLACK	0	1	20%
BROWN	1	10	1%
RED	2	100	2%
ORANGE	3	1,000	3%
YELLOW	4	10,000	4%
GREEN	5	100,000	5%
BLUE	6	1,000,000	6%
VIOLET	7	10,000,000	7%
GRAY	8	100,000,000	8%
WHITE	9	1,000,000,000	9%
GOLD	---	0.1	5%
SILVER	---	0.01	10%

Table 16-3. — Color code for molded capacitors.

used to indicate the value of capacitance in micromicrofarads.

To read the three-dot system correctly, the capacitor must be held so that the arrows point to the right. The first and second dots indicate the first and second significant figures, respectively, and the third dot indicates the multiplier. (See fig. 16-6 (A).) For example, if the three colors were red, green, and orange, the value of the capacitor would be 25,000 micromicrofarads or 0.025 microfarads.

The five-dot system is interpreted by holding the capacitor so that three dots are in the top row and two dots in the bottom row. The three dots in the top row indicate the first three significant figures. The lower left dot in the bottom row is the multiplier, and the lower right dot is the tolerance. (See fig. 16-6 (B).)

The value of a capacitor coded with the six-dot system can be found by holding the capacitor so that the dot arrows point to the right. As shown in figure 16-6 (C), the three dots indicate the first, second, and third significant figures. The lower right dot specifies the multiplier; the

lower middle dot, the tolerance; and the lower left dot, the voltage rating in hundreds of volts. This is the most frequently used color coding system. Assuming the top row of dots, reading from left to right, to be brown, red, and orange, and the bottom row, again reading from left to right, to be blue, green, and red, the capacitance would be 12,300 micromicrofarads; the voltage rating, 600 volts; and the tolerance, 5 percent.

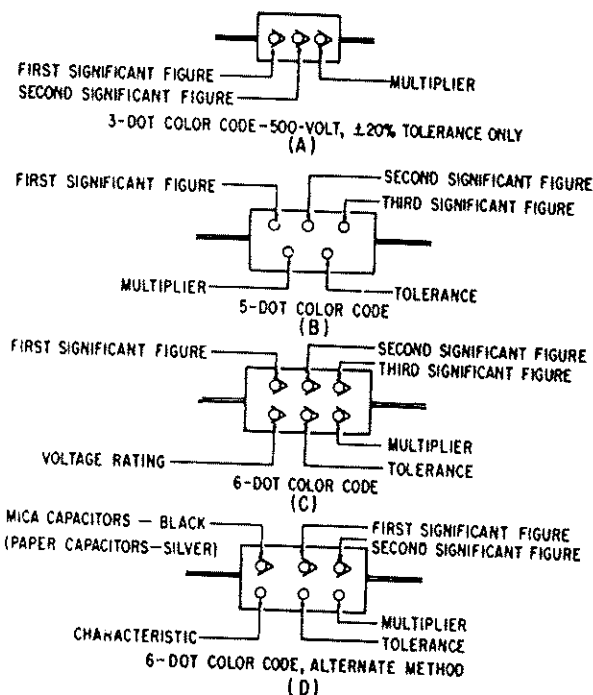


Figure 16-6.—Capacitor color coding. (A) Three-dot color code; (B) five-dot color code; (C) six-dot color code; (D) six-dot color code, alternate method.

The fourth color coding system also uses six dots, arranged in two rows, and again the capacitor must be held so that the arrows point to the right. However, in this system, the top left dot is either black, signifying a mica capacitor; or silver, signifying a paper capacitor. The second and third dots in the top row indicate the first two significant figures; the lower right dot, the multiplier, the lower center dot, the tolerance; and the lower left, the characteristics. "Characteristics" refer to such factors as the type case, dielectric, and temperature coefficient. (Temperature coefficient is the change in capacitance which occurs when a change in temperature takes place.) (See fig. 16-6 (D).)

Ceramic capacitors are color-coded as shown in figure 16-7.

The color code is the same as for molded capacitors except for certain values of multipliers and temperature coefficients. Table 16-4 shows the color code for ceramic capacitors. In the temperature coefficient column, the heading "parts per million per degree centigrade" means the amount the capacitance may change in micromicrofarads for each million micromicrofarads of rated value when the temperature changes by 1 degree centigrade. For example, the figure "-30" in this column would mean that the capacitance of a 1,000,000-micromicrofarad

capacitor would decrease to 999,970 micromicrofarads if the temperature increased 1 degree centigrade.

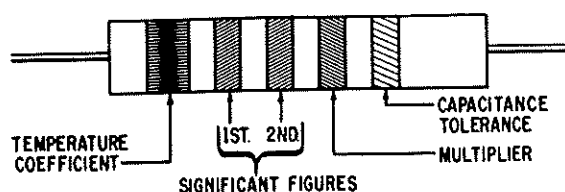


Figure 16-7.—Color code for ceramic capacitors.

Color	Significant figure	Multiplier	Tolerance of capacitance		Temperature coefficient parts per million per degree, centigrade
			Capacitors of value greater than 10 mmfd. in percent	Capacitors of 10 mmfd. or less in mmfd.	
BLACK	0	1	20(M)	2.0(G)	0
BROWN	1	10	1(F)	- - -	-30
RED	2	100	2(G)	- - -	-80
ORANGE	3	1,000	- - -	- - -	-150
YELLOW	4	10,000	- - -	- - -	-220
GREEN	5	100,000	5(J)	0.5(D)	-330
BLUE	6	1,000,000	- - -	- - -	-470
VIOLET	7	10,000,000	- - -	- - -	-750
GRAY	8	.0.01	- - -	0.25(C)	+ 30
WHITE	9	0.1	10(K)	1.0(F)	+550

Table 16-4. — Color code for ceramic capacitors.

Transformers

Chapter 12 of this training course describes several different types of transformers. Since it is essential that all windings be correctly connected, the technician should understand the coding used in marking transformer leads.

Small power transformers, of the size used in electronic equipment, are generally color coded as shown in figure 16-8. In an untapped primary, both leads are black. If the primary is tapped, one lead is common and is colored black, the tap lead is black and yellow, and the

other lead is black and red.

On the transformer secondary, the high-voltage winding has two red leads if untapped, or two red leads and a yellow tap lead if tapped. On the rectifier filament windings, yellow leads are used across the whole winding, and the tap lead is yellow and blue. If there are other filament windings, they will be either green, brown, or slate. The tapped wire will be yellow in combination with one of the colors just named, that is green and yellow, brown and yellow, or slate and yellow.

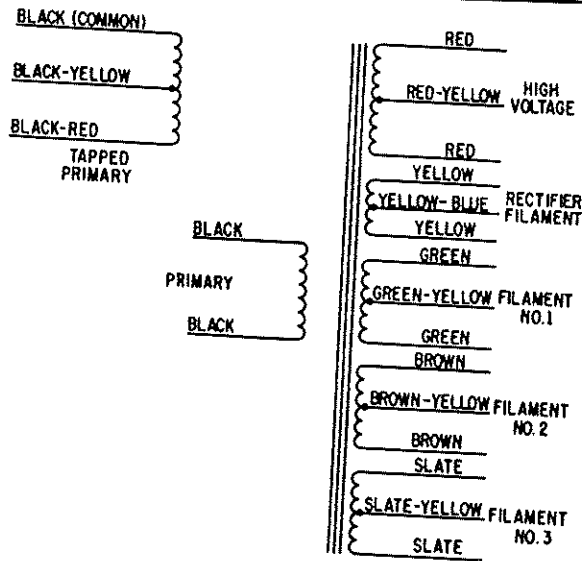


Figure 16-8.—Color coding of small power transformer leads.

The leads of large power transformers, such as those used for shipboard lighting and public utilities, are marked with numbers, letters, or a combination of both. This type of marking is shown in figure 16-9. Terminals for the high-voltage windings are marked H_1 , H_2 , H_3 , and so forth. The increasing numerical subscript designates an increasing voltage. Thus, the voltage between H_1 and H_3 is higher than the voltage between H_1 and H_2 .

The secondary terminals are marked X_1 , X_2 , X_3 , and so forth. There are two types of markings that may be employed on the secondaries. These are shown in figure 16-9. When the H_1 and X_1 leads are brought out on the same side of the transformer (fig. 16-9 (A)), the polarity is called SUBTRACTIVE. The reason this arrangement is called subtractive is as follows: If the H_1 and X_1 leads are connected and a reduced voltage is applied across the H_1 and H_2 leads, the resultant voltage which appears across the H_2 and X_2 leads in the series circuit formed by

this connection will equal the difference in the voltages of the two windings. The voltage of the low-voltage winding opposes that of the high-voltage winding and subtracts from it, hence the term "subtractive polarity."

When the H_1 and X_1 leads are brought out on opposite corners of the transformer (fig. 16-9 (B)), the polarity is ADDITIVE. Navy shipboard transformers have additive polarity. If the H_1 and X_2 leads are connected and a reduced voltage is applied across the H_2 and X_1 leads in the series circuit formed by this connection will equal the sum of the voltages of the two windings. The voltage of the low-voltage winding aids the voltage of the high-voltage winding and adds to it, hence the term "additive polarity."

Polarity markings do not indicate the internal voltage stress in the windings but are useful only in making external connections between transformers, as previously mentioned.

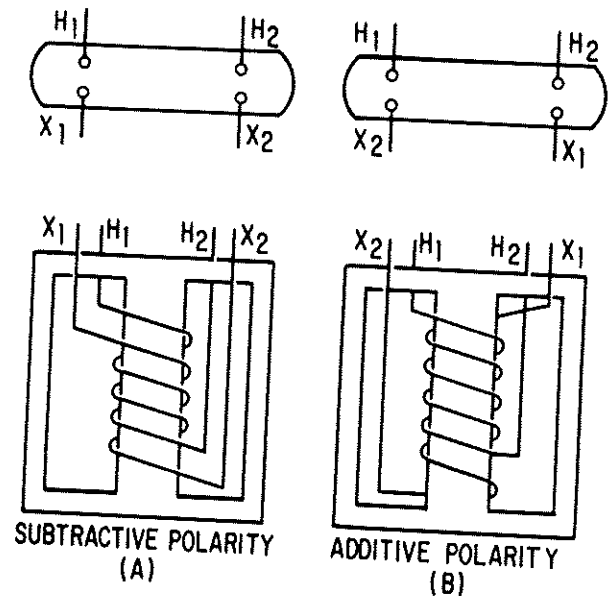


Figure 16-9.—Polarity markings for large transformers.

Drawings

There are many different types of drawings, but it would be impractical to attempt to discuss all of them. Therefore, only those drawings that you, the technician, are apt to use frequently will be explained.

For each ship or aircraft there is a master

electrical drawing. This drawing shows the entire electrical system and includes such information as power generation, distribution, and utilization. You can easily realize that because of size it would be impractical for the entire electrical drawing to be made available each

time information concerning a particular circuit was needed. Therefore, needed sections of this drawing are made available to the technician who maintains that particular part of the system. These sections are usually placed in maintenance manuals.

Many different names are used to describe the various drawings that are constructed to aid in the understanding of electrical systems and equipments. Most all of these drawings are adaptations of some section of the master drawing. Some of the names used to identify particular types of drawings are isometric, expanded, master, wiring, schematic, pictorial, orthographic, and elementary.

The drawings that will be used most often in connection with maintenance work are the wiring diagram and the schematic diagram.

WIRING DIAGRAM

In a wiring diagram the structural parts of a circuit are shown in a simplified form and are

generally arranged so that the physical location of parts is similar to the layout in the actual equipment. An example of this type drawing is shown in figure 16-10, which shows a typical wiring diagram of an automobile electrical system. Through the use of such a diagram, the location and interconnection of parts can be determined. Wiring diagrams are often used in the assembly and maintenance of electrical and electronic circuits in which the placement of parts is critical. For example, the lengths of the leads and the position of a capacitor, coil, or resistor may have a noticeable effect on the performance of a circuit, and this could be clearly specified on a wiring diagram.

SCHEMATIC DIAGRAM

In a schematic diagram (generally called simply a "schematic"), parts are represented by symbols, and may be arranged quite differently from their actual physical arrangement.

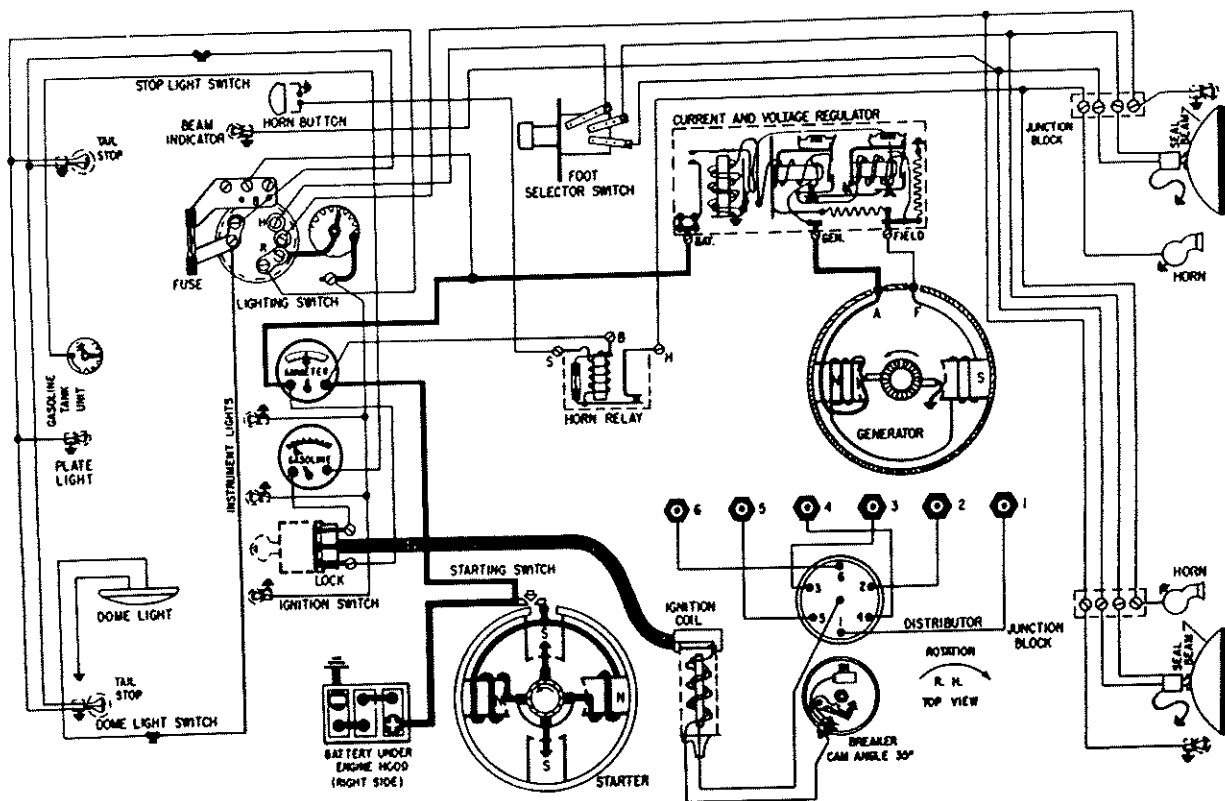


Figure 16-10.—Wiring diagram of automobile electrical system.

BASIC ELECTRICITY

Figure 16-11 is a schematic of the same electrical system shown in figure 16-10. Since this type of diagram is much easier to draw and more

compact than a wiring diagram, it is frequently used in connection with troubleshooting and maintenance, particularly in complicated electrical and electronic equipment.

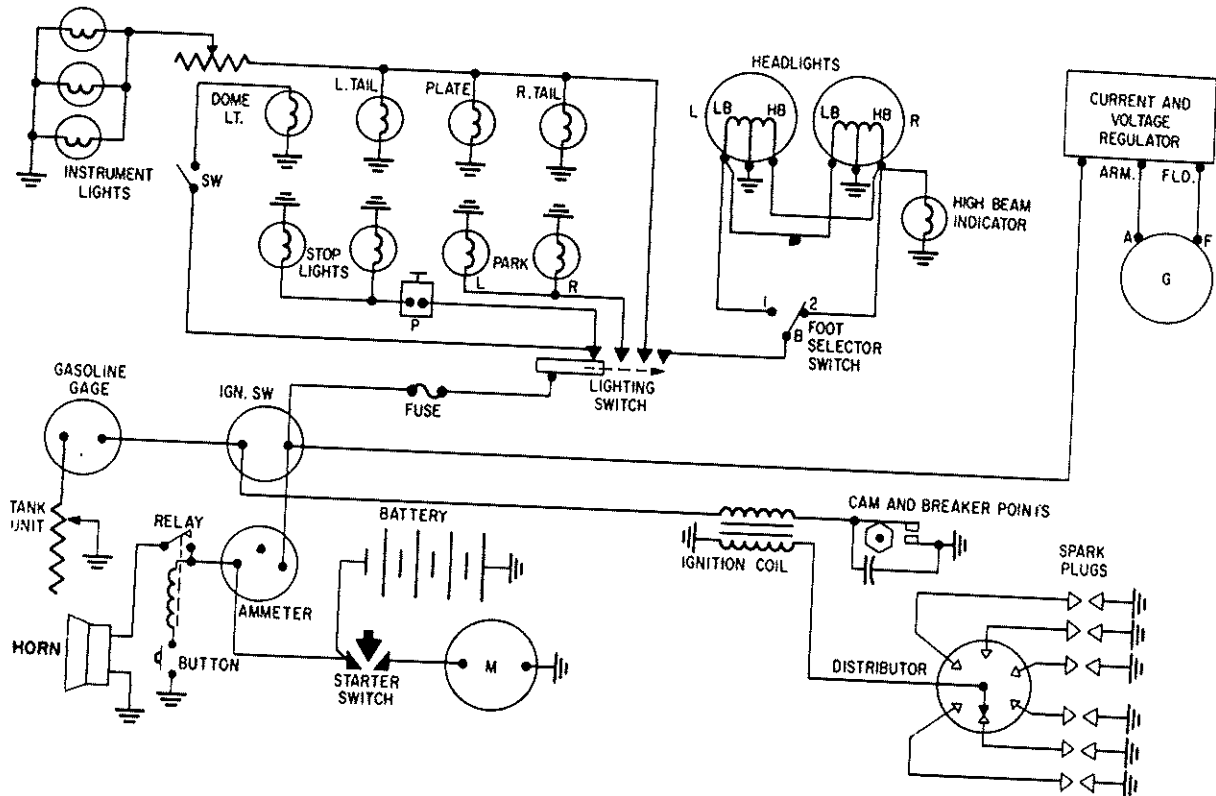


Figure 16-11.—Schematic diagram of automobile electrical system.

Circuit Analysis

You cannot hope to work effectively on a circuit or system you do not understand. Before attempting to make adjustments or correct faults in a circuit, you must first know at least the following:

1. What the circuit is supposed to do in normal operation, and how to operate it.
2. What each part or piece of equipment in the circuit contributes, and how each functions.
3. The location of every part, and routing of conductors.
4. The most likely cause of any given malfunction.
5. The best places to "get into" the circuit for making tests.

If you need any or all of this information, refer to the maintenance manual or master

diagram for a particular circuit or system. These publications are prepared by the builder of the ship or aircraft, and contain the most complete descriptions and explanations available.

Also included in these manuals are wiring and schematic diagrams. After the purpose and operation of a circuit is understood, these diagrams are extremely useful in analyzing the details of its installation and operation. They show actual electrical connections between various parts and points in the circuit. When using these diagrams, you can start at the source of power for a particular circuit, trace along the conductors through control devices such as resistors, coils, capacitors, switches, connecting plugs, terminal points, the load, and finally back to the source. Thus, you gain a mental

picture of the whole circuit before attempting to work on it. (See figs. 16-10 and 16-11.) By thoroughly analyzing the schematic or wiring diagram for a circuit and then operating it to observe the fault, you should have a pretty good idea of **WHAT** and **WHERE** a trouble is before you ever pick up a tool. For instance, suppose you have been told that the headlights on an automobile are not operating properly and you must make repairs.

First, before going to the automobile, you study the schematic diagram (for example, the one in figure 16-11). You determine that the complete headlight circuit is as follows: Starting at the battery, current flows to one side of the starter switch, through the ammeter, to one side of the ignition switch, through a fuse, through the lighting switch when it is down and contacting all four terminals, through the foot selector switch, out terminal 1 or 2, through the selected high-beam (HB) or low-beam (LB) filaments, to ground, and thence back to the battery, one side of which is grounded. When the foot selector switch is in the high-beam (No. 2) position, the beam indicator lamp should be lighted. With the circuit in mind, or carrying a schematic with you, you proceed to the automobile to make an operational check. Upon actuating the lighting switch, you observe that both low beams are lighted. Stepping the foot selector switch to position 2, you observe that the beam indicator lamp is operating, but only the left high-beam headlight is operating. With a glance at the schematic, this indicates that the wiring is sound between terminal 2 and the beam indicator lamp, and between terminal 2 and the left high-beam filament. It also shows that power is being delivered to the right high-beam filament, even though it is not lighting. This indicates that the trouble is in the right headlight. You now know **WHERE** the trouble is, simply by studying the schematic and operating the circuit. You should also have an idea of **WHAT** the trouble is (burned-out high-beam filament). It is now time to **TURN OFF THE POWER**, take up your tools, and go to work on the inoperative headlight.

After exposing the rear terminals of the headlight, you disconnect the wiring and make a continuity check through the high-beam filament with an ohmmeter. To your surprise, the filament checks good. You know that power has

been reaching the right high-beam terminal, because it also supplies power to the left high-beam which works properly. Since power is reaching the filament terminal, and the filament is good, this can only mean that the connection is poor. Cleaning and tightening the connection should correct the fault.

The foregoing procedure is usually referred to as "troubleshooting". Troubleshooting and repair consists in locating the fault and correcting it. Repairing the trouble usually involves the replacement of defective parts, but locating trouble is often a more tedious job, requiring knowledge of the system or equipment plus mechanical know-how. Efficient troubleshooting requires an orderly and systematic procedure.

As a technician, much of your time will be spent troubleshooting the equipment you are required to maintain. This is reason enough for you to become a proficient troubleshooter. Much of the equipment you are required to maintain is quite complex, and you may feel that it is beyond your ability to keep it operative. However, the most complex job will usually become much easier if it is first broken up into successive steps.

Figure 16-12 shows, in chart form, a general troubleshooting procedure. The steps given in blocks 1 through 5 are to be used in locating trouble, and the steps given in blocks 6 and 7 are used in making repairs. Steps 2, 3, 4, and 5 may sometimes be eliminated, but never steps 6 and 7.

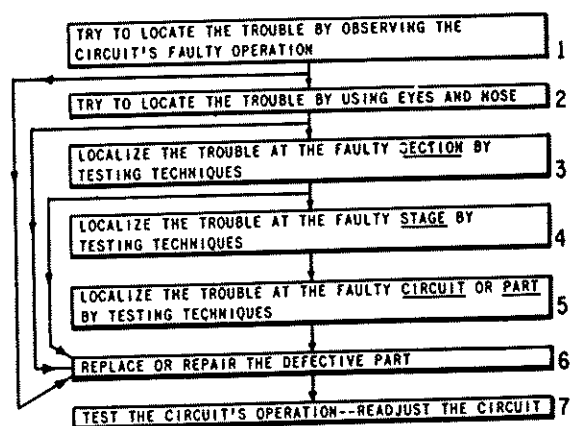


Figure 16-12.—Troubleshooting procedure.

BASIC ELECTRICITY

QUIZ

1. A molded capacitor on which the top row of dots (left to right) is silver, brown, and gray and the bottom row (left to right) is yellow, gold, and orange will have a value of
 - a. 0.018 mfd.
 - b. 18 mfd.
 - c. 0.183 mfd.
 - d. 183 mfd.
2. The electrical symbol used to indicate a potentiometer is
 - a. 
 - b. 
 - c. 
 - d. 
3. The lower left dot in a five-dot capacitor indicates the
 - a. multiplier
 - b. tolerance
 - c. working voltage
 - d. characteristic
4. Small power transformer primary leads are color coded
 - a. red
 - b. black
 - c. green
 - d. yellow
5. The temperature coefficient of a ceramic capacitor is indicated by the
 - a. first dot
 - b. last dot
 - c. first band
 - d. last band
6. A carbon resistor color coded red, blue, green, and gold would indicate a tolerance of
 - a. 2%
 - b. 5%
 - c. 10%
 - d. 20%
7. A carbon resistor color coded brown, black, and silver has a resistance value of
 - a. 0.01Ω
 - b. 0.1Ω
 - c. 1Ω
 - d. 10Ω
8. The secondary high voltage windings of a small power transformer are color coded
 - a. black
 - b. green
 - c. white
 - d. red
9. Before making any adjustments on a faulty circuit, the maintenance man should
 - a. check all resistors and capacitors in the circuit
 - b. make sure he understands what the circuit is supposed to do in normal operation
 - c. check the circuit power supply
 - d. observe the circuit's faulty operation
10. The value of a radial carbon resistor with a red end, blue body, and an orange dot would be
 - a. 26,000 Ω ± 20%
 - b. 6,300 Ω ± 20%
 - c. 3,600 Ω ± 20%
 - d. 62,000 Ω ± 20%
11. The drawings most often used in maintenance work are
 - a. master electrical drawings and schematics
 - b. schematics and wiring diagrams
 - c. wiring diagrams and isometric drawings
 - d. isometric drawings and schematics
12. In a standard circuit drawing 1 milli-ampere, the power rating of a 4-megohm resistor should be
 - a. 3 watts
 - b. 4 watts
 - c. 5 watts
 - d. 6 watts
13. A molded capacitor on which the top row of dots (left to right) is red, violet, and yellow and the bottom row of dots (left to right) is green, silver, and orange will have a voltage rating of
 - a. 200 volts
 - b. 300 volts
 - c. 400 volts
 - d. 500 volts
14. The type of diagram that is consulted to find location and interconnection of parts is called a
 - a. schematic diagram
 - b. master diagram
 - c. wiring diagram
 - d. pictorial diagram

CHAPTER 17

SAFETY

In the performance of your duties as a technician you will install, maintain, and repair electrical and electronic equipment in which dangerously high voltages are frequently present. This work is often done in very limited spaces. Among the hazards of this work are electric shock, electrical fires, harmful gases which are sometimes generated by faulty electrical and electronic devices, and injuries which may be caused by the improper use of tools.

Because of these dangers, you should be aware that the formation of safe and intelligent work habits is fully as important as your knowledge of electrical equipment. One of your primary objectives should be to train yourself to recognize and correct dangerous conditions and to avoid unsafe acts. You must also know the authorized methods for dealing with fires of electric origin, for treating burns, and for giving artificial respiration to persons suffering from electric shock.

Under the heading "Basic Precepts," the *United States Navy Safety Precautions* makes the following statement:

"Most accidents which occur in noncombat operations can be prevented if the full cooperation of personnel is gained and vigilance is exercised to eliminate unsafe acts."

This publication then gives the following general safety rules which apply to personnel in all types of activities:

"Each individual concerned shall strictly observe all safety precautions applicable to his work or duty."

"a. REPORTING UNSAFE CONDITIONS. Each individual concerned shall report any unsafe condition, or any equipment or material which he considers to be unsafe.

"b. WARNING OTHERS. Each individual concerned shall warn others whom he believes to be endangered by known hazards or by failure to observe safety precautions.

"c. PERSONAL PROTECTIVE EQUIPMENT. Each individual concerned shall wear or use protective clothing or equipment of the type approved for the safe performance of his work or duty.

"d. REPORT OF INJURY OR ILL HEALTH. All personnel shall report to their supervisors any injury or evidence of impaired health occurring in the course of work or duty.

"e. EMERGENCY CONDITIONS. In the event of an unforeseen hazardous occurrence, each individual concerned is expected to exercise such reasonable caution as is appropriate to the situation."

Electrical Safety Precautions

EFFECTS OF ELECTRIC SHOCK

Electric shock may cause instant death or may cause unconsciousness, cessation of breathing, and burns of all degrees. If a 60-cycle alternating current is passed through a person from hand to hand or from hand to foot, the effects when current is gradually increased from zero are as follows:

1. At about 1 milliampere (0.001 ampere) the shock can be felt.

2. At about 10 milliamperes (0.010 ampere) the shock is severe enough to paralyze muscles so that a person is unable to release the conductor.

3. At about 100 milliamperes (0.100 ampere) the shock is fatal if it lasts for one second or more.

IT IS IMPORTANT TO REMEMBER THAT CURRENT IS THE SHOCK FACTOR RATHER THAN THE AMOUNT OF VOLTAGE.

You should clearly understand that the resistance of the human body is not great enough to

prevent fatal shock from a voltage of as low as 115 volts. In many cases, voltages less than 115 volts are fatal. When the skin is dry, it has a high resistance. The resistance may be high enough to protect a person from a fatal shock even if one hand touches a high voltage while another part of the body touches the chassis or another ground.

Contact resistance decreases when the skin is moist and body resistance may drop to as low as 300 ohms. With this low body resistance, it can be seen that a very low voltage could supply enough current to cause death.

GENERAL SAFETY PRECAUTIONS IN ELECTRICAL MAINTENANCE

Because of the possibility of injury to personnel, the danger of fire, and possible damage to material, all repair and maintenance work on electrical equipment should be performed only by duly authorized and assigned persons.

When any electrical equipment is to be overhauled or repaired, the main supply switches or cutout switches in each circuit from which power could possibly be fed should be secured in the open position and tagged. The tag should read, "This circuit was ordered open for repairs and shall not be closed except by direct order of...." (usually the person directly in charge of the repairs). After the work has been completed, the tag (or tags) should be removed by the same person.

The covers of fuse boxes and junction boxes should be kept securely closed except when work is being done. Safety devices such as interlocks, overload relays, and fuses should never be altered or disconnected except for replacements. Safety or protective devices should never be changed or modified in any way without specific authorization.

The interlock switch is ordinarily wired in series with the power-line leads to the electronic power supply unit, and is installed on the lid or door of the enclosure so as to break the circuit when the lid or door is opened. A true interlock switch is entirely automatic in action; it does not have to be manipulated by the operator. Multiple interlock switches, connected in series, may be used for increased safety. One switch may be installed on the access door of a device, and another on the cover or the power-supply section. Complex interlock systems are

provided when several separate circuits must be opened for safety.

Because electrical and electronic equipment may have to be serviced without deenergizing the circuits, interlock switches are constructed so that they can be disabled by the technician. However, to minimize the danger of disabling them accidentally, they are generally located in such a manner that a certain amount of manipulation is necessary in order to operate them.

Fuses should be removed and replaced only after the circuit has been deenergized. When a fuse blows, it should be replaced only with a fuse of the same current and voltage ratings. When possible, the circuit should be carefully checked before making the replacement, since the burned-out fuse is often the result of circuit fault.

HIGH-VOLTAGE PRECAUTIONS

Personnel should never work alone near high-voltage equipment. Tools and equipment containing metal parts, such as brushes and brooms, should not be used in any area within four feet of high-voltage circuits or any electric wiring having exposed surfaces. The handles of all metal tools, such as pliers and cutters, should be covered with rubber insulating tape. (The use of plastic or cambric sleeving or of friction tape alone for this purpose is prohibited.) It is also necessary to insulate the shanks of certain screwdrivers (particularly those used inside electronic equipment) with insulating sheaths. Only 3/16 of an inch of the blade need be exposed. Where it is not practicable to tape or otherwise insulate a surface, electricians' insulating varnish may be used.

Before a worker touches a capacitor which is connected to a deenergized circuit, or which is disconnected entirely, he should short-circuit the terminals to make sure that the capacitor is completely discharged. Grounded shorting prods should be permanently attached to workbenches where electronic devices are regularly serviced.

Do not work on any type of electrical apparatus with wet hands or while wearing wet clothing, and do not wear loose or flapping clothing. The use of thin-soled shoes with metal plates or hobnails is prohibited. Safety shoes with nonconducting soles should be worn if available. Flammable articles, such as celluloid cap visors, should not be worn.

Safety Precautions When Using Tools

As a general precaution, be sure that all tools used conform to standards as to quality and type. Use each tool only for the purpose for which it is intended. All tools in active use should be maintained in good repair and all damaged or nonworking tools should be returned to the toolkeeper.

HANDTOOLS

Care must be taken when selecting pliers, side cutters, or diagonal cutters. Pliers or cutters should never be used on nuts or pipe fittings. Always hold the pliers or cutters so that the fingers are not wrapped around the handle in such a way that they can be pinched or jammed if the tool slips. When cutting short pieces, take care that parts of the work do not fly and cause injury. Never put extensions on tool handles to increase leverage.

When selecting a screwdriver for electrical work, be sure that it has a nonconducting handle. The screwdriver selected should be of the proper size to fit the screw and should never be used as a substitute for a punch or a chisel. The points of screwdrivers can be kept in proper shape with a file or a grinding wheel.

Use wrenches only if they are right for the job and only if they are in good condition. An adjustable wrench should be faced so that the movable jaw is located forward in the direction in which the handle is to be turned.

PORTABLE POWER TOOLS

All portable power tools should be inspected before use to see that they are clean, well oiled, and in the proper state or repair. The switches should operate normally, and the cords should be clean and free of defects. The case of any electrically driven power tool should be well grounded; and sparking electric tools should never be used in places where flammable gases or liquids or exposed explosives are present.

Drills must be straight, undamaged, and properly sharpened. Tighten the drill securely in the chuck using the key provided; never secure it with pliers or with a wrench. It is important that the drill be set straight and true in the chuck. The work should be firmly clamped and, if of metal, a center punch should be used to score the material before drilling is started.

Be sure that power cords do not come in contact with sharp objects. The cords should not be allowed to kink, nor should they be allowed to come in contact with oil, grease, hot surfaces, or chemicals. When cords are damaged, they should be replaced instead of being patched with tape.

SHOP MACHINERY

In your work as a technician, you may be required to use a few pieces of shop machinery such as a power grinder or a drill press. In addition to the general precautions on the use of tools, there are several other precautions which should be observed when you work with machinery. The more important ones are:

1. Never remove a guard or cover from a running machine.
2. Never operate mechanical or powered equipment unless you are thoroughly familiar with its controls. When in doubt, consult the appropriate instruction or ask someone who knows.
3. Always make sure that everyone is clear before starting or operating mechanical equipment.
4. Never try to clear jammed machinery without first cutting off the source of power.
5. When hoisting heavy machinery (or equipment) by a chain fall, always keep everyone clear, and guide the hoist with lines attached to the equipment.
6. Never plug in portable electric machinery without insuring that the source is the kind of electricity (a.c. or d.c.) called for on the nameplate of the machine.

First Aid

TREATMENT FOR ELECTRICAL SHOCK

Electric shock is a jarring, shaking sensation resulting from contact with electric circuits or

from the effects of lightning. The victim usually feels that he has received a sudden blow; and if the voltage is sufficiently high, he may become unconscious. Severe burns may appear on the

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skin at the place of contact; muscular spasm can occur, causing him to clasp the apparatus or wire which caused the shock and be unable to turn it loose. Electric shock can kill its victim by stopping the heart or by stopping breathing, or both. It may sometimes damage nerve tissue and result in a slow wasting away of muscles that may not become apparent until several weeks or months after the shock was received.

The following procedure is recommended for rescue and care of shock victims:

1. Remove the victim from electrical contact at once, but **DO NOT ENDANGER YOURSELF**. This can be done by: (1) Throwing the switch if it is nearby; (2) cutting the cable or wires to the apparatus, using an ax with a wooden handle while taking care to protect your eyes from the flash when the wires are severed; (3) use of a dry stick, rope, leather belt, coat, blanket, or any other nonconductor of electricity.

2. Determine whether the victim is breathing. If he is, keep him lying down in a comfortable position. Loosen the clothing about his neck, chest, and abdomen so that he can breathe freely. Protect him from exposure to cold, and watch him carefully.

3. Keep him from moving about. In this condition, the heart is very weak, and any sudden muscular effort or activity on the part of the patient may result in heart failure.

4. Do not give stimulants or opiates. Send for a medical officer at once and do not leave the patient until he has adequate medical care.

5. If the victim is not breathing, it will be necessary to apply artificial respiration without delay, even though he may appear to be lifeless.

RESUSCITATION FROM THE EFFECTS OF ELECTRIC SHOCK

Artificial respiration is the process of promoting breathing by mechanical means. It is used to resuscitate persons whose breathing has stopped, not only as a result of electric shock, but also from causes such as drowning, asphyxiation, strangling, or the presence of a foreign body in the throat.

When a shock victim must be revived, begin artificial respiration as soon as possible. If there is any serious bleeding, stop it first, but do not waste time on anything else. Seconds count; and the longer you wait to begin, the less are the chances of saving the victim. (See fig. 17-1.)

Personnel in all ratings, are required to be able to administer artificial respiration by the back-pressure arm-lift method and the back-pressure hip-lift method.

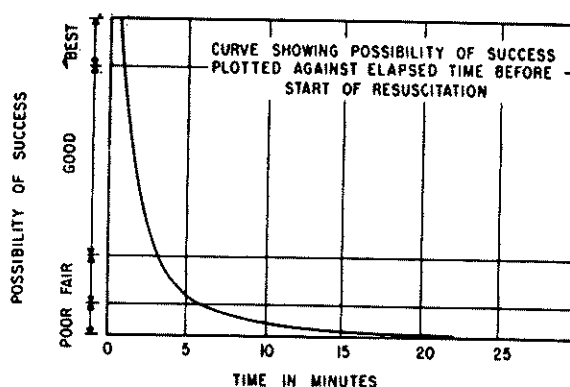


Figure 17-1.—Importance of speed in commencing artificial respiration.

TREATMENT OF BURNS AND WOUNDS

In administering first aid for burns, the objectives are to relieve the pain, to make the patient as comfortable as possible, to prevent infection, and to guard against shock which often accompanies burns of a serious nature.

Any break in the skin is dangerous because it allows germs to enter the wound. Although infection may occur in any wound, it is of particular danger in wounds which do not bleed freely, wounds in which torn tissue or skin falls back into place and so prevents the entrance of air, and wounds which involve crushing of tissues.

Minor wounds should be washed immediately with soap and clean water, dried, and painted

SAFETY

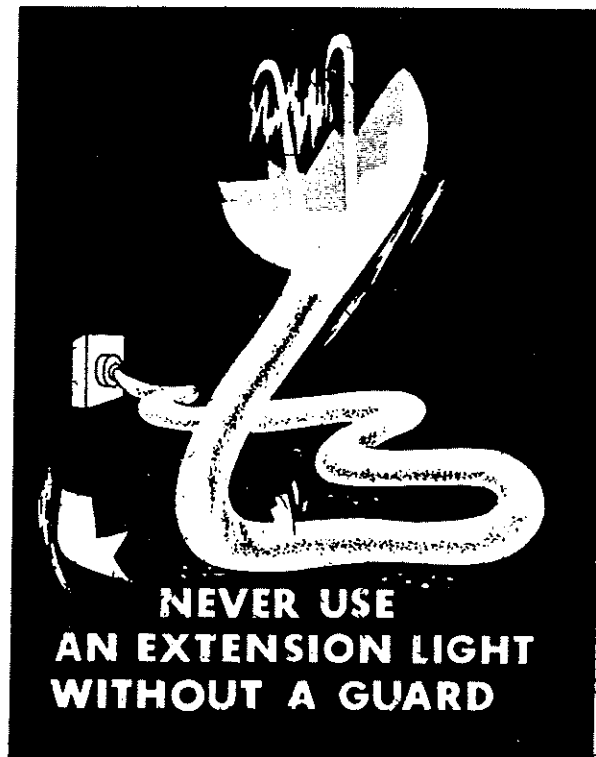
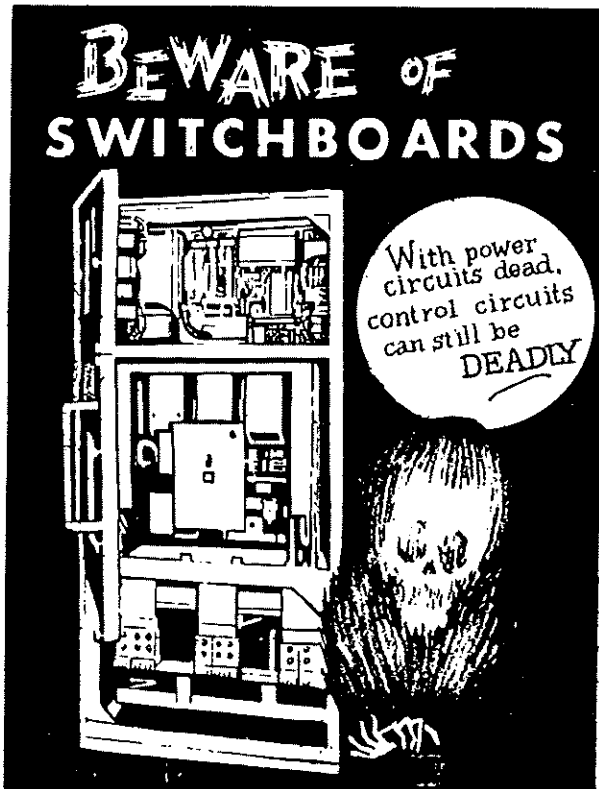
with a mild, nonirritating antiseptic. Benzalkonium chloride tincture, which is now found in most Navy first aid kits, is a good antiseptic; it does not irritate the skin but it effectively destroys many of the micro-organisms which cause infection. (Benzalkonium chloride is commonly sold under the name of Zephiran or Zepherin chloride.) Apply a dressing if necessary.

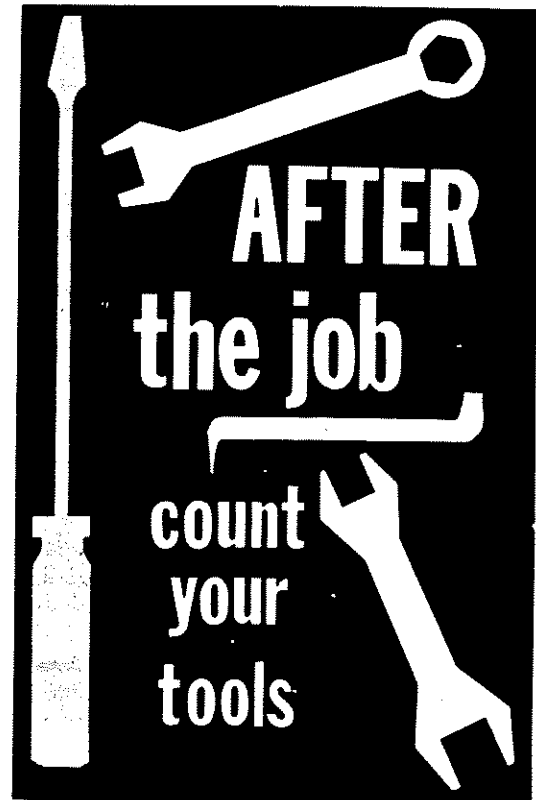
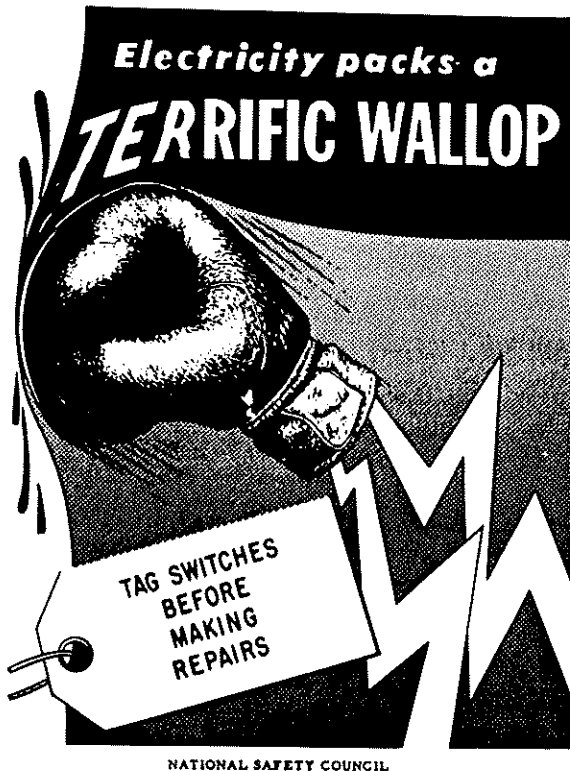
Larger wounds should be treated only by medical personnel. Merely cover the wound with a dry sterile compress and fasten the compress in place with a bandage.

Safety Education

Safety is an all-hand responsibility. It can be done through the use of posters. The job of every person to exercise precaution to Navy makes available numerous safety posters. insure that people will not be injured or killed, Some of these are general in nature and some or equipment damaged or ruined. Safety in-relate to specific types of work. These posters formation is presented in many different ways should be placed in a conspicuous area and as —for example: (1) written material, as given new ones are printed they should replace the in this chapter; (2) safety bulletins; (3) lec-older ones. tures; (4) movies; (5) courses in first aid; and (6) posters.

Every shop in which you work should emphasize safety. One of the ways in which this shop and electrical safety follow. Four of the current posters that relate to





QUIZ

1. It is dangerous to touch a burned-out selenium rectifier when it is hot because
 - a. some of the selenium compound could be absorbed through a skin burn
 - b. direct current could cause shock
 - c. fumes of selenium dioxide could be liberated
 - d. all of the above are correct
2. When using an adjustable wrench, it should be so faced that the movable jaw is located
 - a. forward in the direction in which the handle is turned
 - b. aft of the direction in which the handle is turned
 - c. free of all obstructions
 - d. between the worker and the work to be performed
3. If electrical or electronic equipment is to be repaired, what must be done before the actual work is begun?
 - a. The fuse for the associated circuit must be removed
 - b. The main supply switches must be shorted out
 - c. A man must be stationed nearby with a fire extinguisher
 - d. The main supply switches must be secured open and tagged
4. The handles of all metal tools used for working on electrical circuits should be covered with
 - a. friction tape
 - b. plastic sleeving
 - c. rubber insulating tape
 - d. cambric sleeving
5. To check whether a capacitor is completely discharged, a worker should
 - a. short-circuit the terminals
 - b. take a resistance reading
 - c. lightly tap the leads with his finger
 - d. none of the above are correct
6. The principal hazard(s) when handling and charging batteries is/are due to the danger of
 - a. electrical shock
 - b. asphyxiation
 - c. acid burns and explosion
 - d. acid burns and asphyxiation
7. When fighting an electrical fire, you should use
 - a. foam
 - b. soda and acid
 - c. carbon dioxide
 - d. carbon tetrachloride

SAFETY

8. If you desire to drill a hole in metal, always be sure to
 - a. apply extra pressure to prevent bucking
 - b. use a dull drill and oil
 - c. secure the drill in the chuck with a wrench
 - d. score the material with a center punch
9. Carbon tetrachloride is specifically prohibited as a cleaning agent because it may
 - a. create a fire hazard
 - b. cause dizziness and nausea
 - c. explode if exposed to an electrical spark
 - d. cause blood poisoning
10. Paints and varnishes should be stored in a
 - a. tightly closed metal locker
 - b. sealed fire-resisting room or separate building
 - c. separate building or fire-resisting room which is well-ventilated
 - d. warm and sunlit location
11. Damaged cords for power tools should be
 - a. coated with flux and covered with rubber tape
 - b. repaired with insulating tape
 - c. replaced
 - d. shortened to remove the damaged section
12. Electrical shock is fatal when _____ of current is passed through a person from hand to hand for one second or more.
 - a. 0.10 ampere
 - b. 0.01 ampere
 - c. 1 milliampere
 - d. 10 milliamperes
13. Water is a good firefighting agent on wood, paper,
 - a. cloth, or kerosene
 - b. cloth, or explosives
 - c. oil, or paint
 - d. oil, or gasoline
14. The shock factor of electricity is dependent on the amount of
 - a. resistance
 - b. voltage
 - c. current
 - d. all of the above
15. In case of an electrical fire, the first step is to
 - a. deenergize the circuit
 - b. call the fire department
 - c. extinguish the fire
 - d. notify the proper authority
16. What cleaning agent should be used for cleaning electrical or electronic equipment or parts?
 - a. Alcohol
 - b. Drycleaning solvent
 - c. Carbon tetrachloride
 - d. Turpentine
17. The proper treatment for a person who has received a severe electric shock but is still breathing is to
 - a. give him an opiate to relieve his anxiety
 - b. keep him walking or moving about so that he will not lose consciousness
 - c. apply artificial respiration to assist him in breathing
 - d. keep him lying down

100

CHAPTER 18

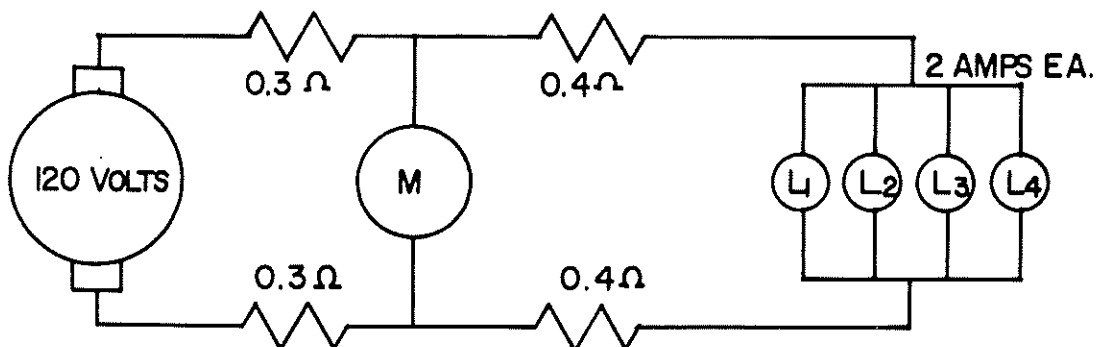
SAMPLE ELECTRICAL PROBLEMS

CHAPTER 18

SAMPLE ELECTRICAL PROBLEMS

Problems on Ohm's Law

1. What is the impressed voltage on an incandescent lamp having a resistance of 440 ohms and a current of $1/2$ amps.
2. What is the impressed voltage on an incandescent lamp having a resistance of 220 ohms and a current of $1/2$ amps.
3. What is the resistance of a toaster if the voltage is 120 and it used 5 amps.
4. What is the amperage if there is 3.5 ohms and 110 volts?
5. A 36 amp line branches into three branch lines with 3, 4, and 0.6 ohms resistance in each line respectively. What is the current through each branch line?
6. 8 Batteries of 6 volts each are connected in series and each gives .75 amps. What is the total amperage?
7. Three motors of 25 amps, 20 amps and 5 amps respectively are connected at the end of a feeder circuit which has .1 ohms on each side. What is the volt drop on the feeder.
8. A small d.c. motor draws 8 amps. A 110 voltage is impressed across the motor. There is a counter electro motive force of 106 volts in the armature at full speed. What is the motors resistance at full speed.
9. 120 Volt source. Motor drawing 10 amps 4 light bulbs drawing 2 amps each. Given section of line and resistances of lines, what is, voltage drop in: A, four sections, B, voltage drop across motor, C, voltage drop across lamps, D, resistance in each lamp.



10. A battery voltage is 12 volts, across the terminals. If when connected in a circuit, the voltage is 9 volts and the current is 6 amps. Find the internal resistance of the battery.

Total Resistance Problems

11. Find the total resistance in a parallel circuit containing, 3, 8, and 12 ohms.
12. Find the total resistance in parallel circuit containing 2, 3, and 4 ohms.
13. Find the resistance across a parallel circuit with 8, 9, 10 and 12 ohms.
14. The resistance of a wire a certain size is 2.517 ohms for 1000 ft. What is the resistance for 400 feet.
15. If 1,000 ft. of copper wire has a resistance of 2.54 ohms, what is the resistance in 400 ft.?
16. If 4 ohms and 3 ohms are connected in parallel across 110 volts of feeder circuit, find the amps and total resistance.
17. If 6, 10, and 12 ohms are connected in parallel, find the joint resistance.
18. 10 ohms, resistance, 3 circuits in series with this which were in parallel. 3, 4 and 6. Find total resistance.
19. Twelve light bulbs of 220 ohms resistance each are connected in parallel. What is the ohms resistance in the circuit and what is the current through the line when all the lights are lit?

BASIC ELECTRICITY

Meter Problems

20. A voltmeter with 250 ohms resistance has a range of 0-10 volts. How much series resistance must it have to have a range of 0-120 volts?
21. The resistance in a voltmeter is 50 ohms. The voltmeter is rated from 0-10 volts. Put the resistance in series with the voltmeter so it will be rated from 0-150 volts.
22. A voltmeter reads 0-5 volts with a resistance of 25 ohms. What total resistance must be added to the circuit to have the meter read from 0-120 volts?
23. Shunt connected to an ammeter is $\frac{1}{99}$ the resistance of the ammeter. Line circuit current is 165 amperes. (a) What is the current thru ammeter. (b) What is the current thru the shunt.

Problems on Power Factor

24. A generator is rated at 10,000 kilowatts and the power factor is .8. What is the KVA value?
25. An alternator with an output of 120 amps and 250 volts and a power factor of 90% operates with another alternator with the same output but a power factor of 75%. What is the kilowatt output?
26. A motor is supplied with a 3-phase 440 volt system. The motor draws 35 amps and has a break HP of 26. Efficiency is 76%. What is the power factor?
27. What is the kilowatt rating of a 3 phase alternator having 550 volts, 300 amps, and a power factor of .80. What would be the kilowatt rating if the power factor was unity.
28. Calculate the current in each supply line of a 3 phase motor fed by 430 line volts and producing 150 SHP. The powerfactor is .8, and the efficiency is 85%.
29. You have two alternators 3 phase 600 volts 1500 KW. If the watt meter indicates 2000 amps, what would be the power factor. Is low factor the cause of poor voltage regulation.

Power Problems

30. What would be the resistance of a light bulb of 60 watts and 120 volts.
31. A lamp has 75 watts and 120 volts. Find the resistance.
32. How many 50 watt lightbulbs can be supported in a line with 120 volts and 30 amps.
33. A generator delivers 115 volts and 215 amps. Find the Kilowatts.
34. A motor draws 20 amps at 220 volts. Find the power used, the horsepower of the motor.
35. A generator produces 44 KW and 110 volts, determine the resistance and the current of the line.
36. Two generators in parallel produce 22 kilowatts each. If the voltage produced is 110 volts, what is the resistance?
37. One motor draws 20 amps and 220 volts. It is run 12 hr./day for 24 days 6 hr./day for 9 days. How many kilowatt hours is this?
38. 100 volt, 40 ohm circuit. Find average power in circuit.
39. Heating element drawing 30 amps, 115 volts. How much power will it draw in 20 minutes.
40. A single phase motor operating on 222 volts and drawing 91 amps has a power factor of 81%. How many kilowatts does the motor use per hour.

Efficiency Problems

41. What is the efficiency of a d.c. generator if the output is 1200 KW and the shaft H.P. of the driving unit is 1800.
42. Switchboard instruments show a 220 KW input to the main propulsion motor which is 98.4% efficient. What is the SHP output of the motor.
43. If a generator has an input efficiency of 89.5% and 35 HP, what is the output in watts.

BASIC ELECTRICITY

44. A generator has an output of 65,000 watts. The output efficiency is 90.5%. Find the input to the armature in H.P.
45. The driving engine of a generator produces 120 HP and the generator is 90% efficient. If it has 220 volts, what is the current?
46. A motor set is 85% efficient and carries a 710 kilowatt load. What is the cost value of deficiency if the set is operated for 24 hours at 4 cent a kilowatt?
47. An engine drives a generator. If the Hp on the engine is 160, find the output of the gear in kilowatts, assuming the generator efficiency is 84%.
48. A generator has an efficiency of 84% and input of 750 HP. What is the output in kilowatts?
49. A pump pumps 500 lbs. of water/min from a depth of 60 ft. The efficiency is 80% and the motor operates on a 220 volt DC line. What is the current across the line?
50. A D.C. electrical circuit supplies 110 volts to 120 lamps having 25 candle power each. The dynamo efficiency is 93% each lamp draws .3 amperes. What is the BHP of the driving unit.
51. A 5 horsepower motor takes 4.8 kilowatts to operate it, what is the efficiency of the motor.

Problems on Impedence

52. A circuit has an inductance of .02 henries in series with a 10 ohm resistance, 110 volts main, and 60 cycles. Find inductive reactance, current flow, voltage drop across inductance, and voltage drop across resistance.
53. Find the impedance of a circuit having .2 henries and 8 ohms at 60 cycles per second.

APPENDIX I
ANSWERS TO QUIZZES

Chapter 1

FUNDAMENTAL CONCEPTS OF ELECTRICITY

- | | | | |
|-------|--------|--------|--------|
| 1. c. | 8. d. | 14. b. | 20. d. |
| 2. d. | 9. c. | 15. d. | 21. d. |
| 3. d. | 10. a. | 16. d. | 22. d. |
| 4. c. | 11. c. | 17. c. | 23. c. |
| 5. c. | 12. b. | 18. a. | 24. d. |
| 6. b. | 13. a. | 19. b. | 25. b. |
| 7. a. | | | |

Chapter 2

BATTERIES

- | | | | |
|-------|--------|--------|--------|
| 1. c. | 6. a. | 11. c. | 16. c. |
| 2. c. | 7. d. | 12. b. | 17. d. |
| 3. d. | 8. b. | 13. b. | 18. c. |
| 4. c. | 9. c. | 14. c. | 19. a. |
| 5. b. | 10. c. | 15. c. | 20. a. |

Chapter 3

THE SIMPLE ELECTRIC CIRCUIT

- | | | | |
|-------|--------|--------|--------|
| 1. a. | 6. c. | 11. b. | 16. b. |
| 2. b. | 7. b. | 12. d. | 17. a. |
| 3. d. | 8. c. | 13. b. | 18. d. |
| 4. a. | 9. b. | 14. b. | 19. b. |
| 5. b. | 10. c. | 15. a. | 20. b. |

Chapter 4

DIRECT-CURRENT SERIES AND PARALLEL CIRCUITS

- | | | | |
|-------|--------|--------|--------|
| 1. c. | 7. b. | 13. d. | 19. b. |
| 2. a. | 8. b. | 14. b. | 20. d. |
| 3. c. | 9. b. | 15. c. | 21. c. |
| 4. b. | 10. a. | 16. a. | 22. d. |
| 5. c. | 11. a. | 17. a. | 23. a. |
| 6. a. | 12. a. | 18. d. | 24. b. |

BASIC ELECTRICITY

Chapter 5

DIRECT-CURRENT COMPOUND AND BRIDGE CIRCUITS

1. b.
2. c.
3. d.
4. b.
5. d.

6. c.
7. c.
8. a.
9. b.
10. d.

11. c.
12. b.
13. a.

Chapter 6

ELECTRICAL CONDUCTORS AND WIRING TECHNIQUES

1. c.
2. d.
3. d.
4. c.
5. a.

6. b.
7. a.
8. c.
9. a.
10. b.

11. c.
12. c.
13. b.
14. d.
15. c.

16. d.
17. a.
18. b.
19. b.
20. a.

Chapter 7

ELECTROMAGNETISM AND MAGNETIC CIRCUITS

1. b.
2. d.
3. b.
4. b.
5. d.
6. c.

7. b.
8. b.
9. a.
10. b.
11. a.

12. c.
13. d.
14. a.
15. a.
16. d.

17. c.
18. c.
19. b.
20. c.
21. c.

Chapter 8

INTRODUCTION TO ALTERNATING-CURRENT ELECTRICITY

1. c.
2. a.
3. d.
4. c.
5. b.
6. d.
7. c.

8. c.
9. b.
10. c.
11. b.
12. b.
13. c.
14. d.

15. b.
16. b.
17. d.
18. a.
19. b.
20. c.
21. c.

22. d.
23. d.
24. a.
25. d.
26. b.
27. c.

Chapter 9

INDUCTANCE AND CAPACITANCE

1. b.
2. c.
3. c.
4. b.
5. a.
6. b.
7. d.

8. d.
9. c.
10. b.
11. c.
12. a.
13. b.

14. a.
15. d.
16. b.
17. a.
18. b.
19. d.

20. b.
21. b.
22. d.
23. a.

Chapter 10

INDUCTIVE AND CAPACITIVE REACTANCE

1. c.
2. c.
3. c.
4. a.
5. a.
6. b.

7. a.
8. a.
9. d.
10. d.
11. a.
12. d.

13. b.
14. d.
15. a.
16. c.
17. b.
18. b.

19. d.
20. a.
21. a.
22. b.
23. a.

CHAPTER 11

BASIC ELECTRICAL INDICATING INSTRUMENTS

- | | | | |
|-------|--------|--------|--------|
| 1. b. | 7. b. | 13. b. | 19. b. |
| 2. c. | 8. c. | 14. c. | 20. d. |
| 3. c. | 9. b. | 15. c. | 21. b. |
| 4. c. | 10. b. | 16. d. | 22. a. |
| 5. b. | 11. a. | 17. a. | 23. c. |
| 6. d. | 12. b. | 18. d. | |

CHAPTER 12

ALTERNATING-CURRENT GENERATORS AND TRANSFORMERS

- | | | | |
|-------|--------|--------|--------|
| 1. c. | 7. d. | 13. c. | 18. b. |
| 2. c. | 8. a. | 14. c. | 19. c. |
| 3. c. | 9. a. | 15. c. | 20. a. |
| 4. d. | 10. b. | 16. b. | 21. c. |
| 5. d. | 11. d. | 17. a. | 22. c. |
| 6. b. | 12. b. | | |

CHAPTER 13

ALTERNATING-CURRENT MOTORS

- | | | | |
|-------|--------|--------|--------|
| 1. d. | 8. b. | 14. c. | 20. c. |
| 2. b. | 9. d. | 15. d. | 21. d. |
| 3. d. | 10. d. | 16. c. | 22. b. |
| 4. b. | 11. b. | 17. a. | 23. d. |
| 5. a. | 12. b. | 18. d. | 24. b. |
| 6. a. | 13. c. | 19. b. | 25. c. |
| 7. a. | | | |

CHAPTER 14

DIRECT-CURRENT GENERATORS

- | | | | |
|-------|--------|--------|--------|
| 1. b. | 8. b. | 15. a. | 22. c. |
| 2. d. | 9. b. | 16. d. | 23. c. |
| 3. b. | 10. c. | 17. d. | 24. a. |
| 4. b. | 11. c. | 18. c. | 25. a. |
| 5. b. | 12. b. | 19. a. | 26. d. |
| 6. d. | 13. a. | 20. c. | 27. a. |
| 7. c. | 14. d. | 21. c. | |

CHAPTER 15

DIRECT-CURRENT MOTORS

- | | | | |
|-------|--------|--------|--------|
| 1. a. | 7. c. | 13. c. | 19. a. |
| 2. d. | 8. d. | 14. d. | 20. d. |
| 3. c. | 9. d. | 15. b. | 21. a. |
| 4. a. | 10. b. | 16. b. | 22. a. |
| 5. b. | 11. b. | 17. b. | 23. d. |
| 6. b. | 12. c. | 18. c. | 24. c. |

CHAPTER 16

ELECTRICAL DRAWINGS AND TECHNICAL MANUALS

- 1. a.
- 2. c.
- 3. a.
- 4. b.

- 5. c.
- 6. b.
- 7. b.
- 8. d.

- 9. d.
- 10. b.
- 11. d.
- 12. d.

- 13. d.
- 14. c.
- 15. c.

CHAPTER 17

SAFETY

- 1. a.
- 2. a.
- 3. d.
- 4. c.
- 5. a.

- 6. c.
- 7. c.
- 8. d.
- 9. b.

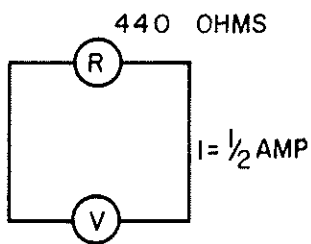
- 10. c.
- 11. c.
- 12. a.
- 13. b.

- 14. c.
- 15. a.
- 16. b.
- 17. d.

APPENDIX II

ANSWERS TO SAMPLE ELECTRICAL PROBLEMS

1.



$$R = 440 \text{ Ohms.}$$

$$E = I \times R$$

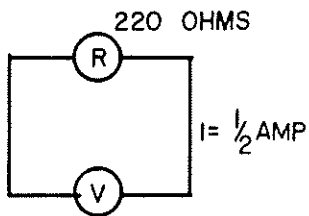
$$E = \frac{1}{2} \times 440$$

Answer:

$$E = \underline{220 \text{ Volts.}}$$

$$\begin{array}{r} 440 \\ .5 \\ \hline 220.0 \end{array}$$

2.



$$R = 220 \text{ Ohms.}$$

$$E = I \times R$$

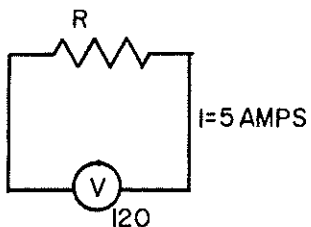
$$E = \frac{1}{2} \times 220$$

Answer:

$$E = \underline{110 \text{ Volts.}}$$

$$\begin{array}{r} 220 \\ .5 \\ \hline 110.0 \end{array}$$

3.



$$E = I \times R$$

$$R = E/I$$

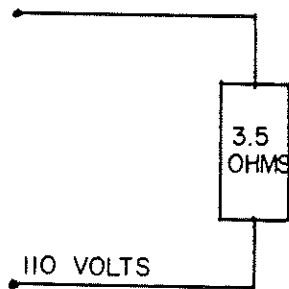
$$R = 120/5$$

Answer:

$$R = \underline{24 \text{ Ohms.}}$$

$$\begin{array}{r} 24 \\ 5 \overline{) 120} \\ \underline{10} \\ 20 \\ \underline{20} \\ 0 \end{array}$$

4.



$$E = IR$$

$$E = \frac{E}{R}$$

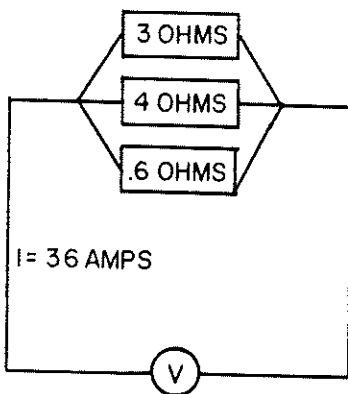
$$I = \frac{110}{3.5}$$

$$I = \underline{31.4285 \text{ AMPS.}}$$

$$35 \overline{) 1100.0000}$$

Handwritten long division showing 35 divided into 1100.0000. The quotient is 31.4285. The steps shown are: 35 goes into 110 three times (105), leaving a remainder of 50. 35 goes into 50 one time (35), leaving a remainder of 15. 35 goes into 150 four times (140), leaving a remainder of 10. 35 goes into 100 two times (70), leaving a remainder of 30. 35 goes into 300 eight times (280), leaving a remainder of 20. 35 goes into 200 five times (175), leaving a remainder of 25.

5.



$$\frac{1}{R_T} = \frac{1}{3} + \frac{1}{4} + \frac{1}{0.6}$$

$$\frac{1}{R_T} = \frac{4 + 3 + 20}{12} = \frac{27}{12}$$

$$R_T = \frac{27}{12}$$

$$R_T = \underline{.4444 \text{ Ohms.}}$$

$$27 \overline{) 12.0000}$$

Handwritten long division showing 27 divided into 12.0000. The quotient is .4444. The steps shown are: 27 goes into 120 four times (108), leaving a remainder of 12. 27 goes into 120 four times (108), leaving a remainder of 12. 27 goes into 120 four times (108), leaving a remainder of 12. 27 goes into 120 four times (108), leaving a remainder of 12.

Figure voltage for entire curcuit which is the same in each branch.

$$E_C = I_C R_T$$

$$E_C = 36 \times 0.4444$$

$$E_C = 15.9984 \text{ Volts.}$$

5. CONTINUED.

Figure current in each branch.

$$I_1 = E_C/R_1 \quad I_1 = \frac{15.9984}{3} = \underline{5.3328 \text{ AMPS.}}$$

$$I_2 = E_C/R_2 \quad I_2 = \frac{15.9984}{4} = \underline{3.9996 \text{ AMPS.}}$$

$$I_3 = E_C/R_3 \quad I_3 = \frac{15.9984}{0.6} = \underline{26.6664 \text{ AMPS.}}$$

MATH

$$\begin{array}{r} 26.6664 \\ 0.6 \overline{)15.9984} \\ \underline{12} \\ 39 \\ \underline{36} \\ 39 \\ \underline{36} \\ 38 \\ \underline{36} \\ 24 \\ \underline{24} \\ 0 \end{array}$$

$$\begin{array}{r} 5.3328 \\ 3 \overline{)15.9984} \\ \underline{15} \\ 9 \\ \underline{9} \\ 9 \\ \underline{9} \\ 8 \\ \underline{6} \\ 24 \\ \underline{24} \\ 0 \end{array}$$

$$\begin{array}{r} 3.9996 \\ 4 \overline{)15.9984} \\ \underline{12} \\ 39 \\ \underline{36} \\ 39 \\ \underline{36} \\ 38 \\ \underline{36} \\ 24 \\ \underline{24} \\ 0 \end{array}$$

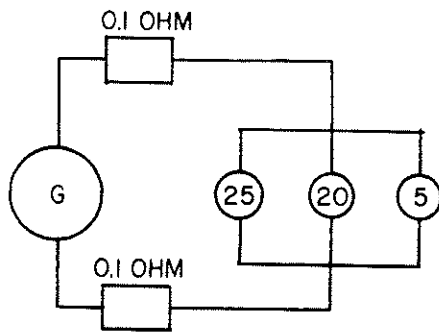
$$\begin{array}{r} 0.4444 \\ \overline{)36} \\ \underline{36} \\ 0 \end{array}$$

6. 8 Batteries, 6 volts, .75 amps each. Total amperage in a series circuit is equal to the amps through any part of the circuit.

.75 Amps - Total circuit amperage.

Since current is a constant in a series circuit.

7.



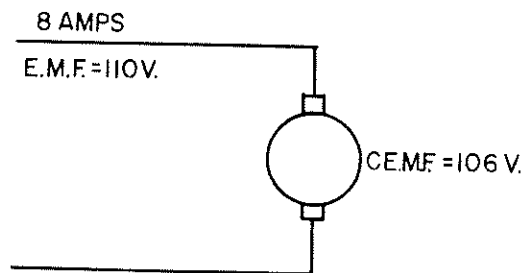
$$I = 25 + 20 + 5 = 50 \text{ Amps.}$$

$$V = IR = 50 (.1 + .1)$$

$$V = 50 (.2) = 10 \text{ Volts.}$$

Answer: 10 Volts.

8.



$$\text{Effective voltage} = \text{EMF} - \text{EMF}$$

$$V = 110 - 106$$

$$V = 4 \text{ Volts.}$$

$$E = I \times R$$

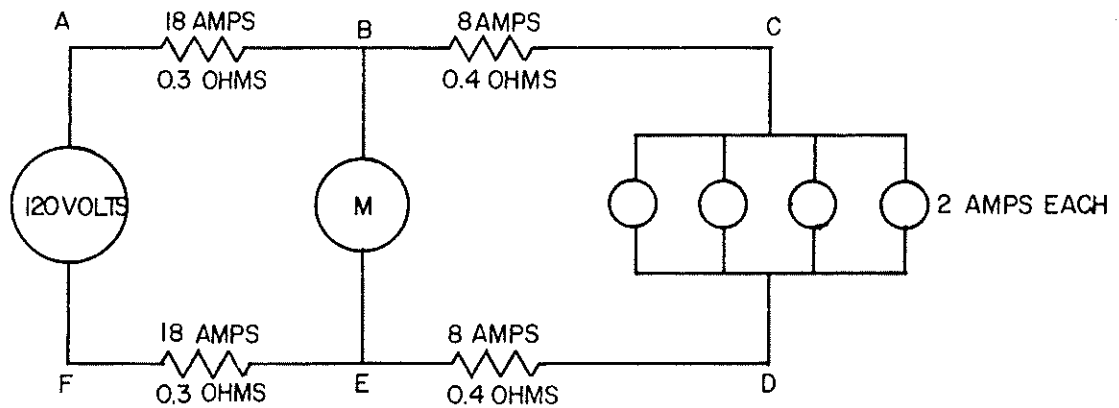
$$4 = 8 \times R$$

$$R = \frac{4}{8}$$

$$R = .5 \text{ Ohms.}$$

Answer: 0.5 OHMS.

9.



A. Find V drop in each section of line.

$$V_{ab} = I \times R = 18 \times .3 = 5.4 \text{ volts.}$$

$$V_{bc} = I \times R = 9 \times .4 = 3.2 \text{ volts.}$$

$$V_{de} = I \times R = 8 \times .4 = 3.2 \text{ volts}$$

$$V_{ef} = I \times R = 18 \times .3 = 5.4 \text{ volts.}$$

B. Voltage drop on motor.

$$V_s - V_d = V_m$$

$$120 - 5.4 - 5.4 = V_m$$

$$109.2 = V_m$$

C. Voltage drop on lamps.

$$V_{be} - V_{drops} = V_{cd}$$

$$109.2 - 3.2 - 3.2 = V_{cd}$$

$$V_{cd} = 102.8 \text{ Volts.}$$

9. CONT'D.

D. Find Resistance of each lamp.

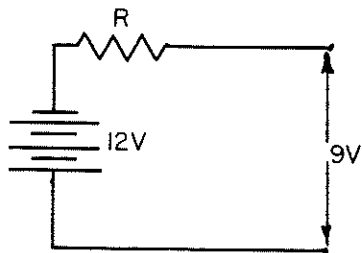
$$V = I \times R$$

$$102.8 = 2 \times R$$

$$R = \frac{102.8}{2}$$

$$R = 51.4 \text{ OHMS.}$$

10.



Circuit current $I = 6a$

Battery voltage drop of $12 - 9 = 3v$

$$E = I R$$

$$3 = 6 R$$

$$R = \frac{3}{6}$$

$$R = \underline{0.5 \text{ OHMS.}}$$

APPENDIX II - ANSWERS TO SAMPLE ELECTRICAL PROBLEMS

14.

$$100 \text{ Ft.} = 2.517 \text{ Ohms Res.}$$

$$\frac{2.517}{1000} = \text{Res. Per foot.}$$

$$\text{Res. per foot} = .002517 \text{ ohms.}$$

$$400 \text{ ft} \times \text{Res. per foot} = \text{Res. for 400 ft.}$$

$$\text{ANS. RES FOR 400 FT.} = 1.0068 \text{ OHMS.}$$

$$\begin{array}{r} .002517 \\ \times 400 \\ \hline 01.006800 \end{array}$$

-OR-

CROSS MULTIPLY

$$\begin{array}{l} 1000 \times = 400 (2.517) \\ x = 400 (2.517) \\ \hline 1000 \end{array}$$

Ratio & Proportion

$$\frac{2.517}{1000} = \frac{x}{400}$$

$$\text{ANSWER R} = \underline{1.0068 \text{ OHMS.}}$$

$$\begin{array}{r} .002517 \\ 1000 \overline{) 2.5170000} \\ \underline{0} \\ 251 \\ \underline{0} \\ 2517 \\ \underline{2000} \\ 5170 \\ \underline{5000} \\ 1700 \\ \underline{1000} \\ 7000 \\ \underline{7000} \end{array}$$

15. Resistance of a wire is directly proportional to the length of the wire.

$$\frac{R_1}{L_1} = \frac{R_2}{L_2}$$

$$\frac{2.54}{1000} = \frac{R_2}{400} \times 2.54$$

$$400 (2.54) = 1000 R_2$$

$$R_2 = 400 \times 2 \left(\frac{2.54}{1000} \right)$$

$$R_2 = 1.016$$

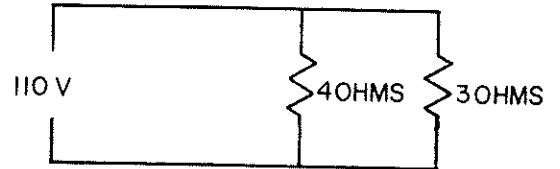
$$\text{Answer: } 1.0160 \text{ Ohms.}$$

$$\begin{array}{r} 2.54 \\ \times 400 \\ \hline 1016.00 \end{array}$$

$$\frac{1016}{1000} = 1.016$$

16.

In a parallel circuit



$$\frac{1}{R_{\text{total}}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \dots \frac{1}{R_n}$$

$$\frac{1}{R_t} = \frac{1}{4} + \frac{1}{3}$$

$$\frac{1}{R_t} = \frac{3}{12} + \frac{4}{12}$$

$$\frac{1}{R_t} = \frac{7}{12}$$

$$R_t = \frac{12}{7} = 1.7142$$

$$\text{Amps} = I = \frac{E}{R} = \frac{110}{1.7142}$$

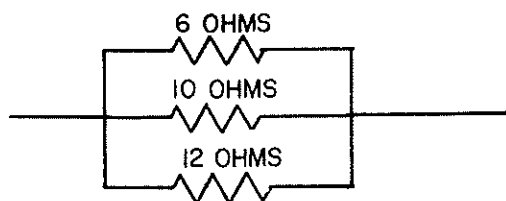
$$I = 64.1698 \text{ Amps.}$$

Answer: 64.1698 Amps.

$$\begin{array}{r} 1.7142 \\ 7 \overline{) 12.0000} \\ \underline{7} \\ 50 \\ \underline{49} \\ 10 \\ \underline{7} \\ 30 \\ \underline{28} \\ 20 \\ \underline{14} \\ 6 \end{array}$$

$$\begin{array}{r} 64.1698 \\ 1.7142 \overline{) 110.0000.0000} \\ \underline{102852} \\ 71480 \\ \underline{68568} \\ 29120 \\ \underline{17142} \\ 119780 \\ \underline{102852} \\ 168280 \\ \underline{154278} \\ 150020 \\ \underline{137136} \\ 12884 \end{array}$$

17.



$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} = \frac{1}{6} + \frac{1}{10} + \frac{1}{12}$$

Common Denominator = 60

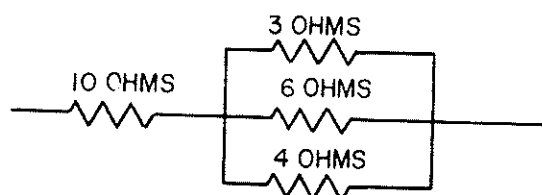
Therefore: $\frac{1}{R_t} = \frac{10}{60} + \frac{6}{60} + \frac{5}{60} = \frac{21}{60}$

$$R = \frac{60}{21} = 2.8571 \text{ Ohms.}$$

Answer: 2.8571 Ohms.

$$\begin{array}{r} 2.8571 \\ 21 \overline{) 60.0000} \\ \underline{42} \\ 180 \\ \underline{168} \\ 120 \\ \underline{105} \\ 150 \\ \underline{147} \\ 30 \\ \underline{21} \\ 9 \end{array}$$

18.



$$(a) \quad \frac{1}{R_T} = \frac{1}{R_3} + \frac{1}{R_4} + \frac{1}{R_6}$$

$$\frac{1}{R_T} = \frac{1}{3} + \frac{1}{4} + \frac{1}{6}$$

$$\frac{1}{R_T} = \frac{4}{12} + \frac{3}{12} + \frac{2}{12} = \frac{9}{12}$$

$$\frac{1}{R_T} = \frac{9}{12}$$

$$R_T = \frac{12}{9} = \frac{4}{3} = 1.3333 \text{ Ohms}$$

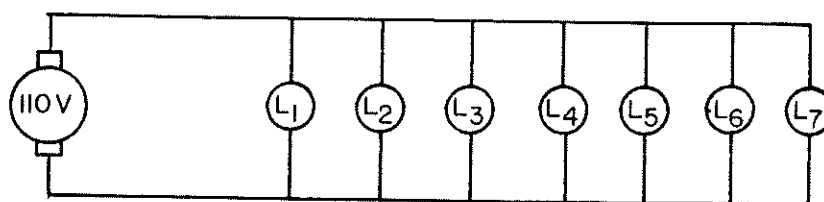
$$(b) \quad R_{\text{Circuit}} = R_{10} + R_T$$

$$R_C = 10 + 1.3333$$

$$R_C = 11.3333$$

Answer: 11.3333 Ohms.

19.



In a parallel Circuit $\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_N}$

$$\frac{1}{R_T} = \frac{1}{220} + \frac{1}{220} + \frac{1}{220} + \frac{1}{220} + \frac{1}{220} + \frac{1}{220} + \frac{1}{220}$$

$$\frac{1}{R_T} = \frac{12}{220}$$

$$R_T = \frac{220}{12} = 18.3333 \text{ Ohms.}$$

$$I = \frac{E}{R} = \frac{110}{18.3333}$$

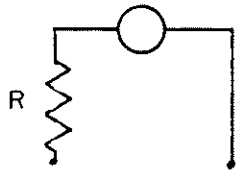
$$I = 6.0000 \text{ Amps.}$$

Answer: $I = 6.000 \text{ Amps.}$

$$\begin{array}{r} 18.3333 \\ 12 \overline{) 220.0000} \\ \underline{12} \\ 100 \\ \underline{96} \\ 40 \\ \underline{36} \\ 40 \\ \underline{36} \end{array}$$

$$\begin{array}{r} 6.000 \\ 18.3333 \overline{) 110.0000} \\ \underline{109.9998} \\ 000020000 \end{array}$$

20.



$$R_V = 250 \text{ } \Omega \text{ for } 0 - 10 \text{ V}$$

$$R_S = ? \text{ } \Omega \text{ for } 0 - 120 \text{ V}$$

$$I_{vm} = \frac{E}{R}$$

$$I_{vm} \text{ (Max. Current in volt meter)}$$

$$I_{vm} = \frac{10}{250} \quad I_{vm} = 0.04 \text{ Amps.}$$

$$R_S \text{ for } 120 \text{ V at } 0.04 \text{ Amps} = R = E/I_{vm}$$

$$R_S = \text{Series Resist) } R_S = \frac{120}{0.04}$$

$$R_S = 3000$$

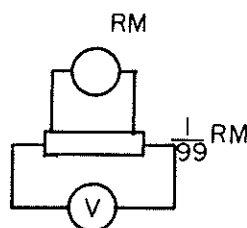
$$R_{\text{needed}} = R_{\text{Req.}} - R_{\text{there}}$$

$$R_{\text{needed}} = 3000 - 250$$

$$R_{\text{needed}} = 2750$$

$$\text{Answer: } R = 2750 \text{ Ohms.}$$

23.



$$\text{(Total Resistance)} \quad \frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

$$\frac{1}{R_T} = \frac{1}{R_m} + \frac{1}{\frac{R_m}{99}}$$

$$\frac{1}{R_T} = \frac{1}{R_m} + \frac{99}{R_m}$$

$$\frac{1}{R_T} = \frac{100}{R_m}$$

$$R_T = \frac{R_m}{100}$$

$$\text{Voltage of Service: } V = I \times R$$

$$V = 165 \times \frac{R_m}{100}$$

$$V = 1.65 R_m$$

(a) Current through Ammeter)

$$V = I \times R$$

$$1.65 R_M = I \times R_M$$

$$I = \frac{1.65 R_M}{R_M}$$

$$I = 1.65 \text{ Amps.}$$

(b) (Current Through Shunt)

$$I = 165 - 1.65 = 163.35 \text{ Amps.}$$

Answer: (a) 1.65 Amps.

(b) 163.35 Amps.

24.

$$F_P = \frac{KW}{KVA}$$

$$KVA = \frac{KW}{F_P}$$

$$KVA = \frac{10,000}{8} = 12500 \text{ Amps.}$$

$$\begin{array}{r} 12500 \\ 8 \overline{) 10,000} \\ \underline{8} \\ 20 \\ \underline{16} \\ 40 \\ \underline{40} \\ 0 \end{array}$$

Answer: 12,500 KVA

25.

Alternator #1 I = 120 amps.
 E = 250 volts.
 PF = .9

$$S = EI$$

$$SP = 120 \times 250 = 30000 \text{ VA (Apparant power)}$$

$$1 \text{ KVA} = 1000 \text{ VA}$$

$$30,000 \text{ VA} = 30 \text{ KVA}$$

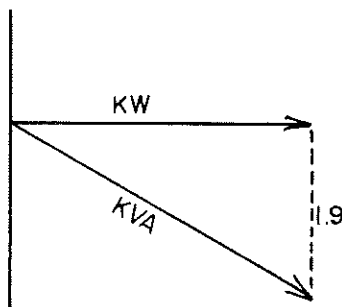
$$\text{Real Power} = KW = KVA \times PF = 30 \times .9 = 27 \text{ KW}$$

Alternatur #2 Has same KVA at .75 PF

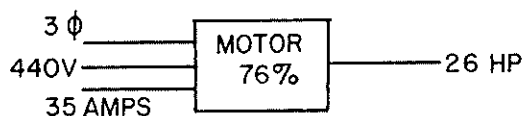
$$\text{Therefore } KW = KVA \times PF = 30 \times .75 = 22.5 \text{ KW}$$

$$\text{Total Output \#1 KW} + \text{\#2 KW} = 27 + 22.5 = 49.5 \text{ KW}$$

ANSWER: 49.5 KW.



26.



$$\text{Efficiency} = \frac{\text{Output}}{\text{Input}}$$

$$.76 = \frac{26}{\text{Input}}$$

$$\text{Input} = \frac{26}{.76}$$

$$\text{Input} = 34.2105 \text{ HP}$$

$$746 \text{ Watts} = 1 \text{ HP}$$

$$\text{Input (watts)} = 34.2105 \times 746$$

$$\text{Input} = 25,521.0330 \text{ Watts}$$

$$1000 \text{ Watts} = 1 \text{ KW}$$

$$\text{Input} = 25.5210 \text{ KW}$$

$$\begin{aligned} \text{Apparant power} &= 3 \text{ E} \times \text{I} \\ \text{Apparant power} &= 1.7321 \times 440 \times 35 \\ \text{Appraent power} &= 26,674.3400 \text{ va} \end{aligned}$$

$$1000 \text{ va} = 1 \text{ KVA}$$

$$\text{Apparent Power} = 26.6743 \text{ KVA}$$

$$F_P = \frac{\text{KW}}{\text{KVA}}$$

$$F_P = \frac{25,5210}{26.6743}$$

$$F_P = .9567$$

$$\text{Answer: Power Factor} = .9567$$

$$\begin{array}{r} 342105 \\ 76 \overline{) 26,000000} \\ \underline{228} \\ 320 \\ \underline{304} \\ 160 \\ \underline{152} \\ 80 \\ \underline{76} \\ 400 \\ \underline{380} \end{array}$$

$$\begin{array}{r} 34.2105 \\ 746 \\ \hline 2052630 \\ 1368420 \\ \hline 2394735 \\ 25521.0330 \end{array}$$

$$\begin{array}{r} 35 \\ 440 \\ \hline 1400 \\ 140 \\ \hline 15400 \end{array}$$

$$\begin{array}{r} 1.7321 \\ 15400 \\ \hline 6928400 \\ 86605 \\ \hline 17321 \\ 26674.3400 \end{array}$$

$$\begin{array}{r} .9567 \\ 26.6743 \overline{) 255210} \\ \underline{2400687} \\ 1514130 \\ \underline{1333715} \\ 1804150 \\ \underline{1600458} \\ 2036920 \\ \underline{1867201} \\ 169719 \end{array}$$

27.

$$F_p = \frac{KW}{KVA}$$

$$KVA = \frac{(53) (550) (300)}{1000} = 165 (1.7321)$$

$$KVA = 285.7965$$

$$KW = KVA \times F_p$$

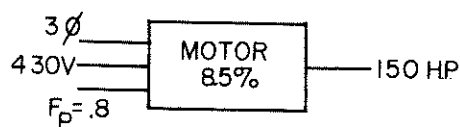
$$KW = 285.7965 (.8) = 228.6372 \text{ KW.}$$

With unity power factor $KW = KVA = 285.7965 \text{ KW.}$

Answer: (a) 228.6372 KW.

(b) 285.7965

28.



$$EFF = \frac{\text{Output}}{\text{Input}}$$

$$.85 = \frac{150}{\text{Input}}$$

$$\text{Input} = \frac{150}{.85}$$

$$\text{Input} = 176.4705$$

$$746 \text{ Watts} = 1 \text{ HP}$$

$$\text{Input (Watts)} = 176.4705 \times 746$$

$$\begin{array}{r} 176.4705 \\ 85 \overline{) 15000.0000} \\ \underline{85} \\ 650 \\ \underline{595} \\ 550 \\ \underline{510} \\ 400 \\ \underline{340} \\ 600 \\ \underline{595} \\ 500 \\ \underline{425} \end{array}$$

APPENDIX II - ANSWERS TO SAMPLE ELECTRICAL PROBLEMS

28 Continued:

Input = 131646.9930 watts

$$\begin{array}{r} 176.4705 \\ 746 \\ \hline 10588230 \\ 7058820 \\ \hline 12352935 \\ 131646.9930 \end{array}$$

Input = 131.6469 KW

$$F_P = \frac{KW}{KVA}$$

$$.8 = \frac{131.6469}{KVA}$$

$$\begin{array}{r} 164.5586 \\ 8 \overline{) 131.6469} \\ 8 \\ \hline 51 \\ 48 \\ \hline 36 \\ 32 \\ \hline 44 \\ 40 \\ \hline 69 \\ 64 \\ \hline 50 \\ 48 \end{array}$$

Apparent Power = 164.5586 KVA.

1000 VA = 1 KVA

VA = 164,558.6

Apparent Power = $\sqrt{3} E_L I_L$

$$164.558.6 = 1.7321 \times 430 \times I$$

$$164.5586 = 744.8030 I$$

$$I = \frac{164,558.6}{744.8030}$$

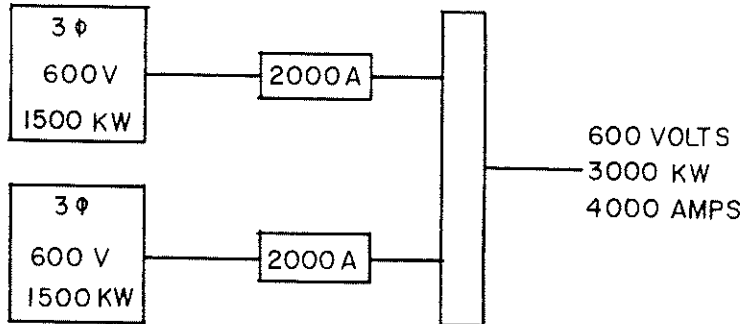
I = 220.9424

Answer: I = 220.9424 Amps.

$$\begin{array}{r} 1.7321 \\ 430 \\ \hline 519630 \\ 69284 \\ \hline 744.8030 \end{array}$$

$$\begin{array}{r} 220.9424 \\ 744.8030 \overline{) 164.558.60000.0000} \\ 14896060 \\ \hline 15598000 \\ 14896060 \\ \hline 70194000 \\ 67032270 \\ \hline 31617300 \\ 29792120 \\ \hline 18251800 \\ 14896060 \\ \hline 33557400 \\ 29792120 \\ \hline 3765320 \end{array}$$

29.



$$\text{Apparent Power} = \sqrt{3} \times E \times I$$

$$\text{Apparent Power} = 1.7321 \times 600 \times 4000$$

$$\text{Apparent Power} = 4,157,040 \text{ va}$$

$$1000 \text{ va} = 1 \text{ KVA}$$

$$\text{Apparent Power (KVA)} = \frac{4,157.040}{1000}$$

$$\text{Apparent Power} = 4157.04 \text{ KVA}$$

$$\begin{array}{r} 4000 \\ \times 600 \\ \hline 2,400,000 \end{array}$$

$$\begin{array}{r} 1.7321 \\ \times 2400000 \\ \hline 6928400000 \\ 34642 \\ \hline 4157040.00000 \end{array}$$

$$F_P = \frac{\text{KW}}{\text{KVA}}$$

$$F_P = \frac{3000}{4157.04}$$

$$F_P = .7216$$

ANSWER: (a) Power Factor = .7216

(b) Low power factor is the cause of poor voltage regulation since a leading or lagging current as indicated by the power factor will distort the main field flux to a greater extent than does unity power factor in such a manner that a lagging power factor increases the main field strength. Thus an increase will cause a rise or fall in voltage.

APPENDIX II - ANSWERS TO SAMPLE ELECTRICAL PROBLEMS

30.

$$P = I \times E$$

$$60 = I \times 120$$

$$I = 60/120$$

$$I = 0.5 \text{ amps.}$$

$$E = I \times R$$

$$120 = 0.5 \times R$$

$$R = \frac{120}{0.5}$$

ANSWER R = 240 OHMS.

$$\begin{array}{r} 120 \overline{) 60.0} \\ \underline{6000} \end{array}$$

$$\begin{array}{r} 240. \\ 5 \overline{) 120.0} \\ \underline{10} \\ 20 \\ \underline{20} \\ 00 \end{array}$$

31.

$$P = I \times E$$

$$75 = I \times 120$$

$$I = \frac{75}{120}$$

$$I = .625 \text{ Amps.}$$

$$E = I \times R$$

$$120 = .625 \times R$$

$$R = \frac{120}{.625}$$

ANSWER: R = 192 OHMS.

$$\begin{array}{r} 120 \overline{) 75.00} \\ \underline{72.0} \\ 300 \\ \underline{240} \\ 600 \\ \underline{600} \end{array}$$

$$\begin{array}{r} 192 \\ .625 \overline{) 120.000.0} \\ \underline{625} \\ 5750 \\ \underline{5625} \\ 1250 \\ \underline{1250} \end{array}$$

32.

$$P = E I$$

$$P = (120) (30)$$

$$P = 3600 \text{ Watts}$$

$$\text{Total Power} = (\text{No. bulbs}) (\text{Power each bulb})$$

$$3600 = N \times 50$$

$$N = \frac{3600}{50}$$

$$N = 72 \text{ BUBLS.}$$

33.

$$P = E I$$

$$P = 115 \times 215 = 24725 \text{ Watts.}$$

$$1000 \text{ Watts} = 1 \text{ KW}$$

$$P = \frac{24725}{1000} = 24.725 \text{ KW.}$$

34.

$$P = EI$$

$$P = 220 \times 20$$

$$P = 4400 \text{ Watts.}$$

$$746 \text{ Watts} = 1 \text{ HP}$$

$$\text{HP} = \frac{P}{746} = \frac{4400}{746}$$

$$\text{HP} = 5.8981 \text{ HP.}$$

APPENDIX II - ANSWERS TO SAMPLE ELECTRICAL PROBLEMS

35.

44 KW 110 Volts.

$$P = \frac{EI}{1000} = \frac{110I}{1000} = 44$$

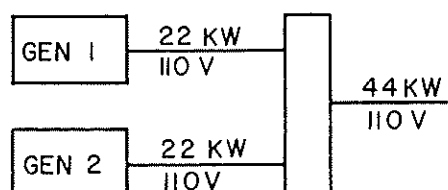
$$I = \frac{44 \times 1000}{110} = \frac{4400}{110} = 400 \text{ AMPS.}$$

$$E = IR$$

$$R = \frac{E}{I} = \frac{110}{400}$$

$$R = .2750 \text{ OHMS.}$$

36.



Total power of both generators is 44 KW or 44,000 watts because 1 KW equals 1000 watts E = 110 Volts.

$$P = 44,000 \text{ watts} = 110 \text{ volts} \times I$$

$$I = 44000/110$$

$$I = \frac{P}{E} = \frac{44,000}{110} = 400 \text{ AMPS.}$$

$$I = 400$$

$$E = IR \quad R = \frac{E}{I} = \frac{110}{400} = .2750 \text{ OHMS.}$$

$$\begin{array}{r} 400 \overline{) 110.0000} \\ \underline{800} \\ 3000 \\ \underline{2800} \\ 2000 \\ \underline{2000} \\ 00 \end{array}$$

BASIC ELECTRICITY

37.

$$I = 20 \text{ AMPS.}$$

$$E = 220 \text{ Volts.}$$

$$12 \text{ Hr/Day for 24 days.}$$

$$6 \text{ Hr /Day for 9 days}$$

$$P = EI = 220 \times 20 = 440 \text{ watts.}$$

$$1 \text{ KW} = 1000 \text{ watts therefore } 4400 \text{ watts} = 4.4 \text{ KW}$$

$$12 \times 24 = 288 \text{ hours.}$$

$$6 \times 9 = 54 \text{ hours.}$$

$$\text{Total Hours} = 342 \text{ Hours.}$$

$$\text{KW} - \text{hours} = \text{KW} \times \text{Hours} = 4.4 \text{ KW} \times 342 \text{ HOURS} = 1504.8 \text{ KW HR.}$$

ANSWER: 1504.8 KW HOURS.

38.

$$P = IE$$

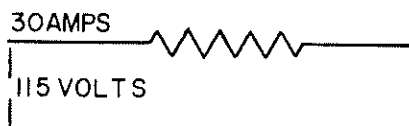
$$I = \frac{E}{R} = \frac{100}{40} = 2.5 \text{ amps.}$$

$$P = 100 \times 2.5 \text{ amps.}$$

$$P = 250 \text{ WATTS.}$$

ANSWER: 250 WATTS.

39.



$$P = I \times E$$

$$P = 30 \times 115$$

$$P = 3450 \text{ Watts.}$$

$$1000 \text{ Watts} = 1 \text{ KW.}$$

$$P = 3.45 \text{ KW.}$$

$$\text{KW} - \text{HR} = 3.45 \times \frac{20}{60}$$

$$\text{KW} - \text{HR} = 1.15$$

ANSWER: 1.15 KW.-HR.

APPENDIX II - ANSWERS TO SAMPLE ELECTRICAL PROBLEMS

40.

$$1\phi, 222\text{ v, } 9\text{ a, } F_p = 81\%$$

$$\text{KVA} = \frac{\text{VA}}{1000} = \frac{222 \times 91}{1000}$$

$$\begin{array}{r} 222 \\ 91 \\ \hline 222 \\ 1998 \\ \hline 20202 \end{array}$$

$$\text{KVA} = \frac{20202}{1000} = 20.202$$

$$\text{KW} = F_p \times \text{KVA} = .81 \times 20.202$$

$$\text{KW} = 16.3636 \text{ KW/HR.}$$

ANSWER: 16.3636 KW/HR.

$$\begin{array}{r} 20.202 \\ 81 \\ \hline 20202 \\ 161616 \\ \hline 16.3636.362 \end{array}$$

41.



$$\text{EFF} = \frac{\text{OUTPUT}}{\text{INPUT}}$$

$$\text{EFF} = \frac{1200 \times 1000}{1800 \times 746}$$

$$\text{EFF} = \frac{1,200,000 \text{ watts}}{1,342,800 \text{ watts}}$$

$$\text{EFF} = .893655 \times 100\%$$

$$\text{EFF} = 89.3655\%$$

$$\begin{array}{r} 746 \\ 1800 \\ \hline 596800 \\ 746 \\ \hline 1,342,800 \end{array}$$

$$\begin{array}{r} .8936550 \\ 13428 \overline{) 12000.000000} \\ \underline{107424} \\ 125760 \\ \underline{120852} \\ 49080 \\ \underline{40284} \\ 87960 \\ \underline{80568} \\ 73920 \\ \underline{67140} \\ 67800 \\ \underline{67140} \\ 6600 \end{array}$$

42.

$$EFF = \frac{OUTPUT}{INPUT}$$

$\frac{220 \text{ KW}}{\text{MOTOR}} \quad \frac{98.4\%}{\text{---}}$

$$.984 = \frac{OUTPUT}{220}$$

$$\text{Output (KW)} = .984 \times 220$$

$$\text{Output (KW)} = 216.48 \text{ KW}$$

$$1000 \text{ watts} = 1 \text{ KW.}$$

$$\text{Output (Watts)} = 216.48 \times 1000$$

$$\text{Output (watts)} = 216.480 \text{ watts.}$$

$$746 \text{ watts} = 1 \text{ HP}$$

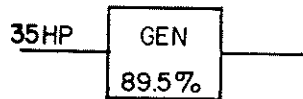
$$\text{Output (HP)} = \frac{\text{Output (watts)}}{746}$$

$$\text{Output (HP)} = \frac{216,480}{746}$$

$$\text{ANSWER: OUTPUT (HP)} = 290.1876 \text{ HP}$$

$$\begin{array}{r}
 290.1876 \\
 746 \overline{) 216,480.0000} \\
 \underline{1492} \\
 6728 \\
 \underline{6714} \\
 140 \\
 \underline{0} \\
 1400 \\
 \underline{746} = \\
 6540 \\
 \underline{5968} \\
 5720 \\
 \underline{5222} \\
 4980 \\
 \underline{4476} \\
 504
 \end{array}$$

43.



If a generator has an input Efficiency of 89.5% and 35 HP, what is the output in watts.

$$1 \text{ HP} = 746 \text{ watts.}$$

$$\text{HP} = 35$$

$$746$$

$$\text{Input (watts)} = 35 (746)$$

$$\text{EFF} = 89.5\%$$

$$35$$

$$3730$$

$$2238$$

$$26110$$

$$\text{Input} = 26,110 \text{ watts.}$$

$$\text{Eff} = \frac{\text{Output}}{\text{Input}}$$

$$26110$$

$$.895 = \frac{\text{Output}}{26,110}$$

$$895$$

$$130550$$

$$2344990$$

$$\text{OUTPUT} = 26,110 \times .895$$

$$208880$$

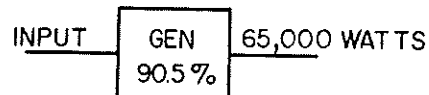
$$23368.450$$

Answer: 23,386.45 watts.

44.

A generator has an output of 65,000 watts. The output efficiency is 90.5%. Find the input to the armature in horsepower.

$$\text{EFF} = \frac{\text{OUTPUT}}{\text{INPUT}}$$



$$.905 = \frac{65000}{\text{Input}}$$

$$\text{Input (watts)} = \frac{65000}{.905}$$

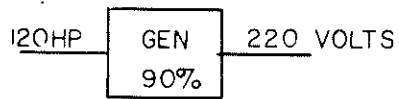
$$\text{Input (watts)} = 71,823.2044 \text{ Watts.}$$

$$746 \text{ Watts} = 1 \text{ HP}$$

$$\text{Input (HP)} = \frac{71,823.2044}{746}$$

ANSWER: INPUT (HP)=94.9238 HP

45.



$$EFF = \frac{\text{Output}}{\text{Input}}$$

$$.9 = \frac{\text{Output}}{120}$$

$$\begin{array}{r} 120 \\ .9 \\ \hline 108.0 \end{array}$$

$$\text{Output (HP)} = .9 (120)$$

$$\text{Output (HP)} = 108 \text{ HP}$$

$$746 \text{ watts} = 1 \text{ HP}$$

$$\text{Output (watts)} = 108 \times 746$$

$$\text{Output (watts)} = 80,568 \text{ watts}$$

$$P = I \times E$$

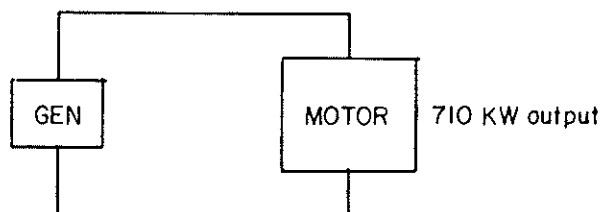
$$80,568 = I \times 220$$

$$I = \frac{80,568}{220}$$

$$\begin{array}{r} 746 \\ 108 \\ \hline 5968 \\ 7460 \\ \hline 80568 \end{array}$$

$$\text{ANSWER } I = 366.2181 \text{ AMPS.}$$

46.



$$EFF = \frac{OUTPUT}{INPUT}$$

$$Input = \frac{Output}{Eff.} = \frac{710}{85} = 835.2941$$

$$Deficiency = Input - Output$$

$$Deefficiency = 835.2941 - 710$$

$$Deefficiency = 125.2941 \text{ KW}$$

$$Cost = KW \times Hr \times Cost \text{ Per KW Hr.}$$

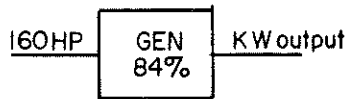
$$Cost = 125.2941 \times 24 \times .04 = \$120.28$$

$$Cost = \$120.28$$

$$ANSWER: \$120.28$$

$$\begin{array}{r} 835.2941 \\ 85 \overline{) 71000.0000} \\ \underline{680} \\ 300 \\ \underline{255} \\ 450 \\ \underline{425} \\ 250 \\ \underline{170} \\ 800 \\ \underline{765} \\ 350 \\ \underline{340} \\ 100 \end{array}$$

47.



$$\text{Efficiency} = \frac{\text{Output}}{\text{Input}}$$

$$.84 = \frac{\text{Output}}{160}$$

$$\text{Output} = .84 (160).$$

$$\text{Output} = 134.40 \text{ HP}$$

$$746 \text{ Watts} = 1 \text{ HP}$$

$$\text{Output (watts)} = 134.40 \times 746$$

$$\text{Output} = 100,262.4 \text{ watts.}$$

$$1000 \text{ Watts} = 1 \text{ KW.}$$

$$\frac{100,262.4}{1000} = \text{Output (KW.)}$$

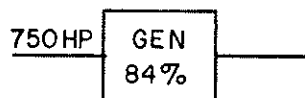
$$\text{Output} = 100.2624 \text{ KW.}$$

$$\text{ANSWER: } 100.2624 \text{ KW.}$$

$$\begin{array}{r}
 .84 \\
 \times 160 \\
 \hline
 5040 \\
 84 \\
 \hline
 134.40
 \end{array}$$

APPENDIX II - ANSWERS TO SAMPLE ELECTRICAL PROBLEMS

48.



1 HP = 746 watts = 0.746 KW.

Engine puts out 750 HP x 746 watts

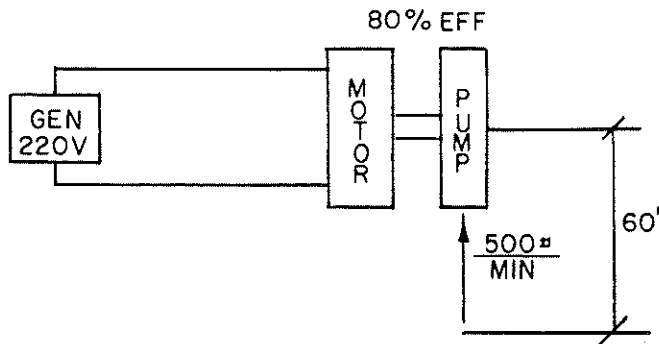
559,500 watts
559.50 KW

Gen. is only 84%, so gen output is 84% of engine input or
559.5 KW x 84%.

ANSWER: 469.980 KW.

MATH:	750	559.5
	<u>746</u>	<u>0.84</u>
	4500	22380
	3000	<u>44760</u>
	<u>5250</u>	469.980KW
	559.50 KW.	

49.



W = Weight x Distance

W = 500 x 60 = 30,000 ft. = lbs/min.

1 Hp = 33000 ft = lbs/min.

$$\text{HP} = \frac{30000}{33000} = .909 \text{ HP}$$

1 HP = 746 Watts.

$$\begin{array}{r} .909 \\ 33 \overline{) 30000} \\ \underline{297} \\ 300 \\ \underline{307} \end{array}$$

$$\begin{array}{r} 746 \\ 909 \\ \underline{6714} \\ 67140 \\ \underline{678.114} \end{array}$$

Watts = .909 x 746 = 678.114

Output.

$$\text{EFF} = \frac{\text{Output}}{\text{Input}}$$

$$\text{Input} = \frac{\text{Output}}{\text{Eff.}} = \frac{678.114}{80}$$

Input = 847.6425 = Power in Watts.

P Watts = V x I

$$I = \frac{P}{V} = \frac{847.6425}{220}$$

I = 3.85292 Amps

ANSWER: I = 3.8529 AMPS.

$$\begin{array}{r} 847.6425 \\ 8 \overline{) 6781.1400} \\ \underline{64} \\ 38 \\ \underline{32} \\ 61 \\ \underline{56} \\ 51 \\ \underline{48} \\ 34 \\ \underline{32} \\ 20 \\ \underline{16} \\ 40 \end{array}$$

50.

$$P \text{ consumed} = EI \quad I = (120 \text{ candles}) (.03)$$

$$P = 110 \times (0.3) \times 120 = 3960 \text{ watts.}$$

$$1 \text{ HP} = 746 \text{ watts}$$

$$\text{HP of Dynamo} = \frac{3960}{746} \times 0.93 = \frac{3960}{693.78}$$

ANSWER: 5.7078 HP.

51.



$$746 \text{ Watts} = 1 \text{ HP}$$

$$\text{Output (watts)} = 5 \times 746$$

$$\text{Output (watts)} = 3730 \text{ watts}$$

$$1000 \text{ watts} = 1 \text{ KW}$$

$$\text{Output (KW)} = \frac{3730}{1000}$$

$$\text{Output (KW)} = 3.73 \text{ KW}$$

$$\text{Efficiency} = \frac{\text{Output}}{\text{Input}}$$

$$\text{Efficiency} = \frac{3.73}{4.8}$$

$$\text{Efficiency} = .7770$$

$$\text{Efficiency} = 77.7\%$$

ANSWER: 77.7%

52.

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

$$X_L = 2\pi fL = (3.1416) (2) (60) (0.02)$$

Inductive Reactance

$$X_C = 0$$

$$Z = \sqrt{10^2 + (7.5398)^2}$$

$$Z = \sqrt{100 + 56.8485}$$

$$Z = \sqrt{156.8485}$$

$$Z = 12.5239 \text{ Ohms.}$$

$$I_C = \frac{E_C}{Z} = \frac{110}{12.5239} = 8.7832 \text{ AMPS.}$$

$$E_L = I R_L = \frac{110}{12.5239} \times 7.5398 = 66.2235 \text{ Volts.}$$

$$E_R = I_L R_R \quad E_R = 8.7832 \times 10 = 87.832 \text{ Volts.}$$

$$\text{ANSWER: (a) } X_L = 7.5398 \text{ Ohms.}$$

$$(b) I = 8.7832 \text{ Amps.}$$

$$(c) V_L = 66.2235 \text{ Volts.}$$

$$(d) V_R = 87.832 \text{ Volts.}$$

APPENDIX II - ANSWERS TO SAMPLE ELECTRICAL PROBLEMS

53.

$$L = .2 \text{ Henries} \quad 60 \text{ cps}$$

$$R = 8 \text{ Ohms.}$$

$$X_L = 2\pi FL \quad X_L = (3.1416) (60) (.2) = (3.1416) (12)$$

$$X_L = 24 (3.1414)$$

$$X_L = 75.3984$$

$$Z = \sqrt{8^2 + (75.3984)^2}$$

$$Z = \sqrt{64 + 5684.9187}$$

$$Z = 75.8216$$

$$\text{ANSWER: } Z = 75.8216 \text{ OHMS.}$$

$$\begin{array}{r} 75.3984 \\ 75.3984 \\ \hline 3015936 \\ 6031872 \\ 6785856 \\ 2261952 \\ 3769920 \\ 5277888 \\ \hline 5684.91872256 \end{array}$$

54.

$$\text{Circular mils} = (\text{Diameter in Mils})^2$$

$$1 \text{ mil} = .001 \text{ inches} \quad \frac{5}{.001} = 500 \text{ Mils.}$$

$$\text{CM} = (500)^2$$

$$\text{ANSWER: } 250,000 \text{ CIRCULAR MILS.}$$

55 (a)

3000 Rpm - 2 Pole Generator

$$F = \frac{NP}{120} = \frac{2 \times 3000}{120} = \frac{6000}{120}$$

$$120 \overline{) 6000} \quad 50$$

ANSWER: FREQUENCY = 50 CPS.

(b)

For 56 poles at 50 cps.

$$F = \frac{NP}{120}$$

$$N = \frac{120 F}{NP} = \frac{120 \times 50}{56}$$

$$\begin{array}{r} 120 \\ \times 50 \\ \hline 6000 \end{array}$$

$$N = \frac{6000}{56}$$

$$N = 107.1428$$

$$56 \overline{) 6000.0000} \quad 107.1428$$

ANSWER: N = 107.1428 RPM

APPENDIX II - ANSWERS TO SAMPLE ELECTRICAL PROBLEMS

56. Energy = Power x Time (KW - HR)

$$P = I \times E$$

$$P = 30 \times 115$$

$$P = 3,450 \text{ watts}$$

$$1000 \text{ watts} = 1 \text{ KW}$$

$$P = \frac{3450}{1000}$$

$$P = 3.45 \text{ KW.}$$

$$\text{Energy} = \text{Power} \times \text{Time}$$

$$\text{Energy} = \text{for 20 minutes} = 1/3 \text{ hour.}$$

$$\text{Energy} = 3.45 \times 1/3$$

$$\text{Energy} = 1.15 \text{ KW HR.}$$

$$\text{ANSWER: } E = 1.15 \text{ KW HR.}$$

APPENDIX III

ELECTRICAL TERMS AND FORMULAS

Terms

- AGONIC.**--An imaginary line of the earth's surface passing through points where the magnetic declination is 0° ; that is, points where the compass points to true north.
- AMMETER.**--An instrument for measuring the amount of electron flow in amperes.
- AMPERE.**--The basic unit of electrical current.
- AMPERE-TURN.**--The magnetizing force produced by a current of one ampere flowing through a coil of one turn.
- AMPLIDYNE.**--A rotary magnetic or dynamo-electric amplifier used in servomechanism and control applications.
- AMPLIFICATION.**--The process of increasing the strength (current, power, or voltage) of a signal.
- AMPLIFIER.**--A device used to increase the signal voltage, current, or power, generally composed of a vacuum tube and associated circuit called a stage. It may contain several stages in order to obtain a desired gain.
- AMPLITUDE.**--The maximum instantaneous value of an alternating voltage or current, measured in either the positive or negative direction.
- ARC.**--A flash caused by an electric current ionizing a gas or vapor.
- ARMATURE.**--The rotating part of an electric motor or generator. The moving part of a relay or vibrator.
- ATTENUATOR.**--A network of resistors used to reduce voltage, current, or power delivered to a load.
- AUTOTRANSFORMER.**--A transformer in which the primary and secondary are connected together in one winding.
- BATTERY.**--Two or more primary or secondary cells connected together electrically. The term does not apply to a single cell.
- BREAKER POINTS.**--Metal contacts that open and close a circuit at timed intervals.
- BRIDGE CIRCUIT.**--The electrical bridge circuit is a term referring to any one of a variety of electric circuit networks, one branch of which, the "bridge" proper, connects two points of equal potential and hence carries no current when the circuit is properly adjusted or balanced.
- BRUSH.**--The conducting material, usually a block of carbon, bearing against the commutator or sliprings through which the current flows in or out.
- BUS BAR.**--A primary power distribution point connected to the main power source.
- CAPACITOR.**--Two electrodes or sets of electrodes in the form of plates, separated from each other by an insulating material called the dielectric.
- CHOKE COIL.**--A coil of low ohmic resistance and high impedance to alternating current.
- CIRCUIT.**--The complete path of an electric current.
- CIRCUIT BREAKER.**--An electromagnetic or thermal device that opens a circuit when the current in the circuit exceeds a predetermined amount. Circuit breakers can be reset.
- CIRCULAR MIL.**--An area equal to that of a circle with a diameter of 0.001 inch. It is used for measuring the cross section of wires.
- COAXIAL CABLE.**--A transmission line consisting of two conductors concentric with and insulated from each other.
- COMMUTATOR.**--The copper segments on the armature of a motor or generator. It is cylindrical in shape and is used to pass power into or from the brushes. It is a switching device.
- CONDUCTANCE.**--The ability of a material to conduct or carry an electric current. It is the reciprocal of the resistance of the material, and is expressed in mhos.
- CONDUCTIVITY.**--The ease with which a substance transmits electricity.
- CONDUCTOR.**--Any material suitable for carrying electric current.
- CORE.**--A magnetic material that affords an easy path for magnetic flux lines in a coil.
- COUNTER E.M.F.**--Counter electromotive force; an e.m.f. induced in a coil or armature that opposes the applied voltage.
- CURRENT LIMITER.**--A protective device similar to a fuse, usually used in high amperage circuits.
- CYCLE.**--One complete positive and one complete negative alternation of a current or voltage.
- DIELECTRIC.**--An insulator; a term that refers to the insulating material between the plates of a capacitor.

BASIC ELECTRICITY

- DIODE.**--Vacuum tube--a two element tube that contains a cathode and plate; semiconductor--a material of either germanium or silicon that is manufactured to allow current to flow in only one direction. Diodes are used as rectifiers and detectors.
- DIRECT CURRENT.**--An electric current that flows in one direction only.
- EDDY CURRENT.**--Induced circulating currents in a conducting material that are caused by a varying magnetic field.
- EFFICIENCY.**--The ratio of output power to input power, generally expressed as a percentage.
- ELECTROLYTE.**--A solution of a substance which is capable of conducting electricity. An electrolyte may be in the form of either a liquid or a paste.
- ELECTROMAGNET.**--A magnet made by passing current through a coil of wire wound on a soft iron core.
- ELECTROMOTIVE FORCE (e.m.f.).**--The force that produces an electric current in a circuit.
- ELECTRON.**--A negatively charged particle of matter.
- ENERGY.**--The ability or capacity to do work.
- FARAD.**--The unit of capacitance.
- FEEDBACK.**--A transfer of energy from the output circuit of a device back to its input.
- FIELD.**--The space containing electric or magnetic lines of force.
- FIELD WINDING.**--The coil used to provide the magnetizing force in motors and generators.
- FLUX FIELD.**--All electric or magnetic lines of force in a given region.
- FREE ELECTRONS.**--Electrons which are loosely held and consequently tend to move at random among the atoms of the material.
- FREQUENCY.**--The number of complete cycles per second existing in any form of wave motion; such as the number of cycles per second of an alternating current.
- FULL-WAVE RECTIFIER CIRCUIT.**--A circuit which utilizes both the positive and the negative alternations of an alternating current to produce a direct current.
- FUSE.**--A protective device inserted in series with a circuit. It contains a metal that will melt or break when current is increased beyond a specific value for a definite period of time.
- GAIN.**--The ratio of the output power, voltage, or current to the input power, voltage, or current, respectively.
- GALVANOMETER.**--An instrument used to measure small d-c currents.
- GENERATOR.**--A machine that converts mechanical energy into electrical energy.
- GROUND.**--A metallic connection with the earth to establish ground potential. Also, a common return to a point of zero potential. The chassis of a receiver or a transmitter is sometimes the common return, and therefore the ground of the unit.
- HENRY.**--The basic unit of inductance.
- HORSEPOWER.**--The English unit of power, equal to work done at the rate of 550 foot-pounds per second. Equal to 746 watts of electrical power.
- HYSTERESIS.**--A lagging of the magnetic flux in a magnetic material behind the magnetizing force which is producing it.
- IMPEDANCE.**--The total opposition offered to the flow of an alternating current. It may consist of any combination of resistance, inductive reactance, and capacitive reactance.
- INDUCTANCE.**--The property of a circuit which tends to oppose a change in the existing current.
- INDUCTION.**--The act or process of producing voltage by the relative motion of a magnetic field across a conductor.
- INDUCTIVE REACTANCE.**--The opposition to the flow of alternating or pulsating current caused by the inductance of a circuit. It is measured in ohms.
- INPHASE.**--Applied to the condition that exists when two waves of the same frequency pass through their maximum and minimum values of like polarity at the same instant.
- INVERSELY.**--Inverted or reversed in position or relationship.
- ISOGONIC LINE.**--An imaginary line drawn through points on the earth's surface where the magnetic deviation is equal.
- JOULE.**--A unit of energy or work. A joule of energy is liberated by one ampere flowing for one second through a resistance of one ohm.
- KILO.**--A prefix meaning 1,000.
- LAG.**--The amount one wave is behind another in time; expressed in electrical degrees.
- LAMINATED CORE.**--A core built up from thin sheets of metal and used in transformers and relays.
- LEAD.**--The opposite of LAG. Also, a wire or connection.

ELECTRICAL TERMS AND FORMULAS

- LINE OF FORCE.**—A line in an electric or magnetic field that shows the direction of the force.
- LOAD.**—The power that is being delivered by any power producing device. The equipment that uses the power from the power producing device.
- MAGNETIC AMPLIFIER.**—A saturable reactor type device that is used in a circuit to amplify or control.
- MAGNETIC CIRCUIT.**—The complete path of magnetic lines of force.
- MAGNETIC FIELD.**—The space in which a magnetic force exists.
- MAGNETIC FLUX.**—The total number of lines of force issuing from a pole of a magnet.
- MAGNETIZE.**—To convert a material into a magnet by causing the molecules to rearrange.
- MAGNETO.**—A generator which produces alternating current and has a permanent magnet as its field.
- MEGGER.**—A test instrument used to measure insulation resistance and other high resistances. It is a portable hand operated d-c generator used as an ohmmeter.
- MEGOHM.**—A million ohms.
- MICRO.**—A prefix meaning one-millionth.
- MILLI.**—A prefix meaning one-thousandth.
- MILLIAMMETER.**—An ammeter that measures current in thousandths of an ampere.
- MOTOR-GENERATOR.**—A motor and a generator with a common shaft used to convert line voltages to other voltages or frequencies.
- MUTUAL INDUCTANCE.**—A circuit property existing when the relative position of two inductors causes the magnetic lines of force from one to link with the turns of the other.
- NEGATIVE CHARGE.**—The electrical charge carried by a body which has an excess of electrons.
- NEUTRON.**—A particle having the weight of a proton but carrying no electric charge. It is located in the nucleus of an atom.
- NUCLEUS.**—The central part of an atom that is mainly comprised of protons and neutrons. It is the part of the atom that has the most mass.
- NULL.**—Zero.
- OHM.**—The unit of electrical resistance.
- OHMMETER.**—An instrument for directly measuring resistance in ohms.
- OVERLOAD.**—A load greater than the rated load of an electrical device.
- PERMALLOY.**—An alloy of nickel and iron having an abnormally high magnetic permeability.
- PERMEABILITY.**—A measure of the ease with which magnetic lines of force can flow through a material as compared to air.
- PHASE DIFFERENCE.**—The time in electrical degrees by which one wave leads or lags another.
- POLARITY.**—The character of having magnetic poles, or electric charges.
- POLE.**—The section of a magnet where the flux lines are concentrated; also where they enter and leave the magnet. An electrode of a battery.
- POLYPHASE.**—A circuit that utilizes more than one phase of alternating current.
- POSITIVE CHARGE.**—The electrical charge carried by a body which has become deficient in electrons.
- POTENTIAL.**—The amount of charge held by a body as compared to another point or body. Usually measured in volts.
- POTENTIOMETER.**—A variable voltage divider; a resistor which has a variable contact arm so that any portion of the potential applied between its ends may be selected.
- POWER.**—The rate of doing work or the rate of expending energy. The unit of electrical power is the watt.
- POWER FACTOR.**—The ratio of the actual power of an alternating or pulsating current, as measured by a wattmeter, to the apparent power, as indicated by ammeter and voltmeter readings. The power factor of an inductor, capacitor, or insulator is an expression of their losses.
- PRIME MOVER.**—The source of mechanical power used to drive the rotor of a generator.
- PROTON.**—A positively charged particle in the nucleus of an atom.
- RATIO.**—The value obtained by dividing one number by another, indicating their relative proportions.
- REACTANCE.**—The opposition offered to the flow of an alternating current by the inductance, capacitance, or both, in any circuit.
- RECTIFIERS.**—Devices used to change alternating current to unidirectional current. These may be vacuum tubes, semiconductors such as germanium and silicon, and dry-disk rectifiers such as selenium and copper-oxide.
- RELAY.**—An electromechanical switching device that can be used as a remote control.
- RELUCTANCE.**—A measure of the opposition that a material offers to magnetic lines of force.
- RESISTANCE.**—The opposition to the flow of current caused by the nature and physical dimensions of a conductor.
- RESISTOR.**—A circuit element whose chief characteristic is resistance; used to oppose the flow of current.

BASIC ELECTRICITY

RETENTIVITY.—The measure of the ability of a material to hold its magnetism.

RHEOSTAT.—A variable resistor.

SATURABLE REACTOR.—A control device that uses a small d-c current to control a large a-c current by controlling core flux density.

SATURATION.—The condition existing in any circuit when an increase in the driving signal produces no further change in the resultant effect.

SELF-INDUCTION.—The process by which a circuit induces an e.m.f. into itself by its own magnetic field.

SERIES-WOUND.—A motor or generator in which the armature is wired in series with the field winding.

SERVO.—A device used to convert a small movement into one of greater movement or force.

SERVOMECHANISM.—A closed-loop system that produces a force to position an object in accordance with the information that originates at the input.

SOLENOID.—An electromagnetic coil that contains a movable plunger.

SPACE CHARGE.—The cloud of electrons existing in the space between the cathode and plate in a vacuum tube, formed by the electrons emitted from the cathode in excess of those immediately attracted to the plate.

SPECIFIC GRAVITY.—The ratio between the density of a substance and that of pure water, at a given temperature.

SYNCHROSCOPE.—An instrument used to indicate a difference in frequency between two a-c sources.

SYNCHRO SYSTEM.—An electrical system that gives remote indications or control by means of self-synchronizing motors.

TACHOMETER.—An instrument for indicating revolutions per minute.

TERTIARY WINDING.—A third winding on a transformer or magnetic amplifier that is used as a second control winding.

THERMISTOR.—A resistor that is used to compensate for temperature variations in a circuit.

THERMOCOUPLE.—A junction of two dissimilar metals that produces a voltage when heated.

TORQUE.—The turning effort or twist which a shaft sustains when transmitting power.

TRANSFORMER.—A device composed of two or more coils, linked by magnetic lines of force, used to transfer energy from one circuit to another.

TRANSMISSION LINES.—Any conductor or system of conductors used to carry electrical energy from its source to a load.

VARS.—Abbreviation for volt-ampere, reactive.

VECTOR.—A line used to represent both direction and magnitude.

VOLT.—The unit of electrical potential.

VOLTMETER.—An instrument designed to measure a difference in electrical potential, in volts.

WATT.—The unit of electrical power.

WATTMETER.—An instrument for measuring electrical power in watts.

Formulas

Ohm's Law for d-c Circuits

$$I = \frac{E}{R} = \frac{P}{E} = \sqrt{\frac{P}{R}}$$

$$R = \frac{E}{I} = \frac{P}{I^2} = \frac{E^2}{P}$$

$$E = IR = \frac{P}{I} = \sqrt{PR}$$

$$P = EI = \frac{E^2}{R} = I^2R$$

Resistors in Series

$$R_T = R_1 + R_2 \dots$$

Resistors in Parallel Two resistors

$$R_T = \frac{R_1 R_2}{R_1 + R_2}$$

More than two

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

ELECTRICAL TERMS AND FORMULAS

R-L Circuit Time Constant equals
 $\frac{L \text{ (in henrys)}}{R \text{ (in ohms)}} = t \text{ (in seconds), or}$

$\frac{L \text{ (in microhenrys)}}{R \text{ (in ohms)}} = t \text{ (in microseconds)}$

R-C Circuit Time Constants equals
 $R \text{ (ohms)} \times C \text{ (farads)} = t \text{ (seconds)}$
 $R \text{ (megohms)} \times C \text{ (microfarads)} = t \text{ (seconds)}$
 $R \text{ (ohms)} \times C \text{ (microfarads)} = t \text{ (microseconds)}$
 $R \text{ (megohms)} \times C \text{ (micromicrofarads)} = t \text{ (microseconds)}$

Comparison of Units in Electric and Magnetic Circuits.

	Electric circuit	Magnetic circuit
Force	Volt, E or e.m.f.	Gilberts, F, or m.m.f.
Flow	Ampere, I	Flux, Φ , in maxwells
Opposition	Ohms, R	Reluctance, R
Law	Ohm's law, $I = \frac{E}{R}$	Rowland's law $\Phi = \frac{F}{R}$
Intensity of force	Volts per cm. of length	$H = \frac{1.257IN}{L}$, gilberts per centimeter of length
Density	Current density— for example, amperes per cm ² .	Flux density—for example, lines per cm ² ., or gaussess

Capacitors in Series
Two capacitors

$$C_T = \frac{C_1 C_2}{C_1 + C_2}$$

More than two

$$\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} \dots$$

Capacitors in Parallel

$$C_T = C_1 + C_2 \dots$$

Capacitive Reactance

$$X_c = \frac{1}{2\pi f C}$$

Impedance in an R-C Circuit (Series)

$$Z = \sqrt{R^2 + X_c^2}$$

Inductors in Series

$$L_T = L_1 + L_2 \dots \text{(No coupling between coils)}$$

Inductors in Parallel
Two inductors

$$L_T = \frac{L_1 L_2}{L_1 + L_2} \text{(No coupling between coils)}$$

More than two

$$\frac{1}{L_T} = \frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3} \dots \text{(No coupling between coils)}$$

Inductive Reactance

$$X_L = 2\pi f L$$

Q of a Coil

$$Q = \frac{X_L}{R}$$

Impedance of an R-L Circuit (series)

$$Z = \sqrt{R^2 + X_L^2}$$

Impedance with R, C, and L in Series

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

Parallel Circuit Impedance

$$Z = \frac{Z_1 Z_2}{Z_1 + Z_2}$$

Sine-Wave Voltage Relationships
Average value

$$E_{ave} = \frac{2}{\pi} \times E_{max} = 0.637 E_{max}$$

BASIC ELECTRICITY

Effective or r.m.s. value

$$E_{\text{eff}} = \frac{E_{\text{max}}}{\sqrt{2}} = \frac{E_{\text{max}}}{1.414} = 0.707E_{\text{max}} = 1.11E_{\text{ave}}$$

Maximum value

$$E_{\text{max}} = \sqrt{2}E_{\text{eff}} = 1.414E_{\text{eff}} = 1.57E_{\text{ave}}$$

Voltage in an a-c circuit

$$E = IZ = \frac{P}{I \times P.F.}$$

Current in an a-c circuit

$$I = \frac{E}{Z} = \frac{P}{E \times P.F.}$$

Power in A-C Circuit

Apparent power = EI

True power

$$P = EI \cos \theta = EI \times P.F.$$

Power factor

$$P.F. = \frac{P}{EI} = \cos \theta$$

$$\cos \theta = \frac{\text{true power}}{\text{apparent power}}$$

Transformers

Voltage relationship

$$\frac{E}{E} = \frac{N}{N} \text{ or } E = E \times \frac{N}{N}$$

Current relationship

$$\frac{I_p}{I_s} = \frac{N_s}{N_p}$$

Induced voltage

$$E_{\text{eff}} = 4.44 BA f N 10^{-8}$$

Turns ratio equals

$$\frac{N_p}{N_s} = \sqrt{\frac{Z_p}{Z_s}}$$

Secondary current

$$I_s = I_p \frac{N_p}{N_s}$$

Secondary voltage

$$E_s = E_p \frac{N_s}{N_p}$$

Three Phase Voltage and Current Relationships
With wye connected windings

$$E_{\text{line}} = 1.732E_{\text{coil}} = \sqrt{3}E_{\text{coil}}$$

$$I_{\text{line}} = I_{\text{coil}}$$

With delta connected windings

$$E_{\text{line}} = E_{\text{coil}}$$

$$I_{\text{line}} = 1.732I_{\text{coil}}$$

With wye or delta connected winding

$$P_{\text{coil}} = E_{\text{coil}} I_{\text{coil}}$$

$$P_t = 3P_{\text{coil}}$$

$$P_t = 1.732E_{\text{line}} I_{\text{line}}$$

(To convert to true power multiply by $\cos \theta$)

Synchronous Speed of Motor

$$\text{r.p.m.} = \frac{120 \times \text{frequency}}{\text{number of poles}}$$

APPENDIX IV

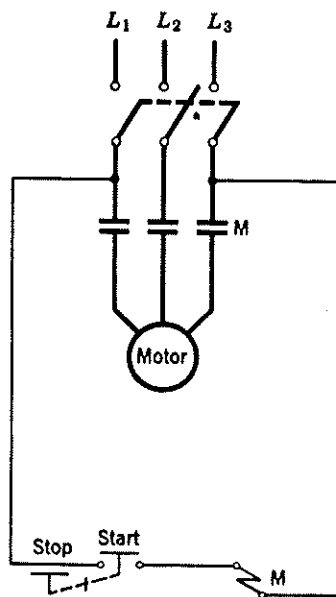
COMMON ABBREVIATIONS AND LETTER SYMBOLS

Term	Abbreviation or Symbol
alternating current (noun)	a.c.
alternating-current (adj.)	a-c
ampere	a.
area	A
audiofrequency (noun)	AF
audiofrequency (adj.)	A-F
capacitance	C
capacitive reactance	X_c
centimeter	cm.
conductance	G
coulomb	Q
counterelectromotive force	c.e.m.f.
current (d-c or r.m.s. value)	I
current (instantaneous value)	i
cycles per second	c.p.s.
dielectric constant	K, k
difference in potential (d-c or r.m.s. value)	E
difference in potential (instantaneous value)	e
direct current (noun)	d.c.
direct-current (adj.)	d-c
electromotive force	e.m.f.
frequency	f
henry	h.
horsepower	hp.
impedance	Z
inductance	L
inductive reactance	X_L
kilovolt	kv.
kilovolt-ampere	kv.-a.
kilowatt	kw.
kilowatt-hour	kw.-hr.
magnetic field intensity	H
magnetomotive force	m.m.f.
megohm	M
microampere	μ a.
microfarad	μ f.
microhenry	μ h.
micromicrofarad	$\mu\mu$ f.
microvolt	μ v.
milliampere	ma.
millihenry	mh.
milliwatt	mw.
mutual inductance	M
power	P
resistance	R
revolutions per minute	r.p.m.
root mean square	r.m.s.
time	t
torque	T
volt	v.
watt	w.

APPENDIX V

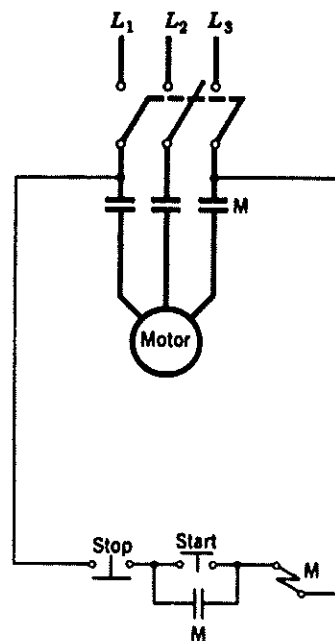
MOTOR CONTROL CIRCUIT DIAGRAMS

UNDERVOLTAGE RELEASE — This control circuit provides for the automatic disconnection of the motor from the line in case of low voltage and its automatic reconnection when the voltage is restored.

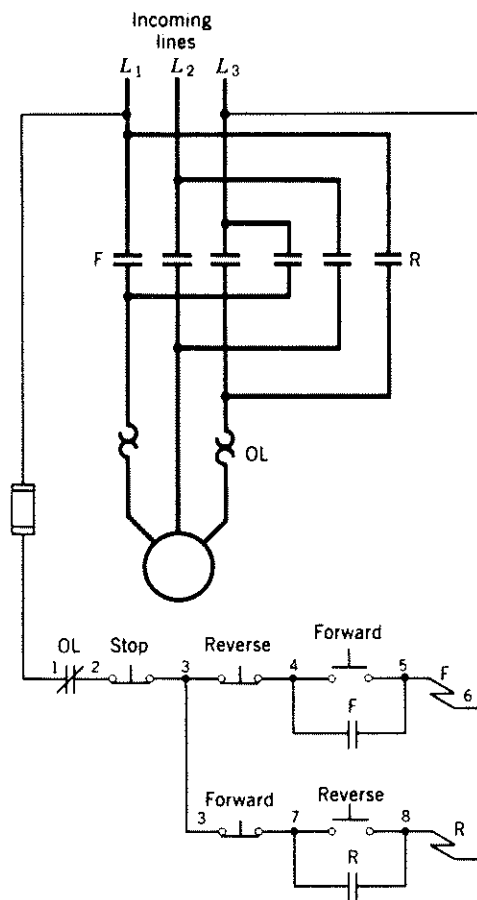


Elementary diagram of a controller that provides undervoltage release.

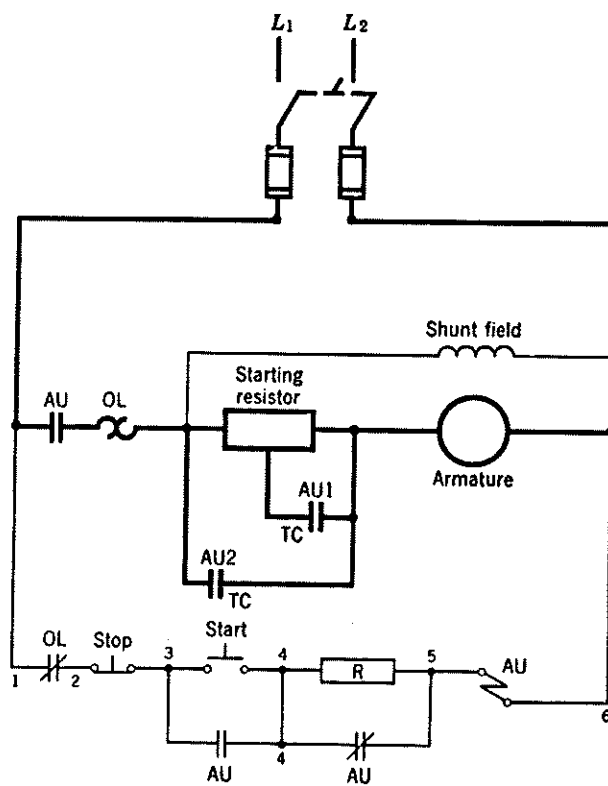
UNDervoltage PROTECTION — This control removes the motor and control circuit from the line, in the event of undervoltage, and prevents automatic restarting when the voltage is restored.



Elementary diagram of a controller that provides undervoltage protection.

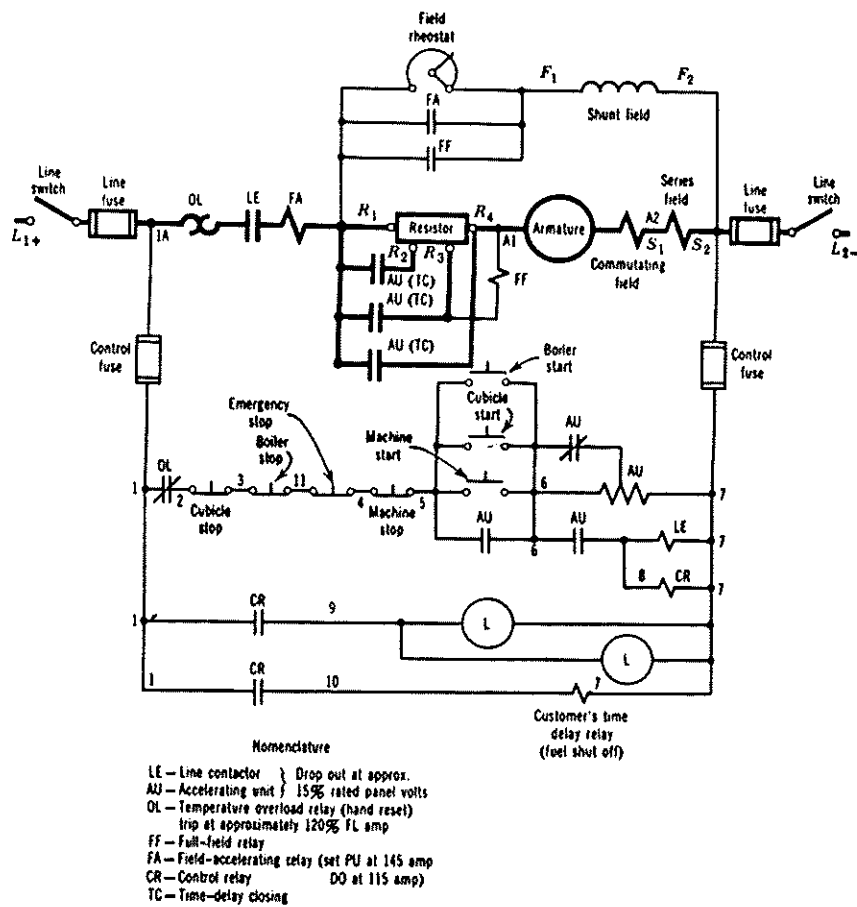


Elementary wiring diagram of a reversing across-the-line starter with overload and undervoltage protection (General Electric Co.).



Definite-time starter with an accelerating unit.

BASIC ELECTRICITY



Elementary diagram of a controller for a forced draft fan used in a power

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